GEOLOGY OF THE HIMALAYAS

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EDITOR'S NOTE TO REGIONAL GEOLOGY SERIES

The aim of this series on Regional Geology is to add to the available geological literature concise descriptions of large structural units, independent of national boundaries.

It is important that the personal opinion of an author, formed by his work and experience in the structural unit he describes, comes clearly to the attention of the reader. Theorizing about the geological history of a particular kind of structure too often does not take into account the great diversity of the observed phenomena, and then generalizes in an unwarranted way. We aim to give a better basis to these general concepts and thereby stimulate a deeper understanding of the relations between different kinds of structures.

Some of the books describe classical territory where new work has brought new conceptions, others are concerned with hitherto relatively unknown regions, but always the surveys are presented from a fresh aspect.

L. U. de Sitter

Geology of

THE HIMALAYAS

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1964

INTERSCIENCE PUBLISHERS
a division of John Wiley & Sons Ltd
LONDON · NEW YORK · SYDNEY

Cover photo: "Mani Stones" at Tangboche by D. Reist
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Library of Congress Catalog Card Number 64-8902

Printed in Switzerland by Orell Füssli, Arts graphiques S. A., Zurich

PREFACE

During the International Geological Congress in Copenhagen, 1960, L. Ulbo de Sitter suggested to me that I prepare a Geology of the Himalayas for the series of books on regional geology. In spite of my great interest in this beautiful mountain range I was rather reluctant to accept the assignment. There were certainly many geologists with a much longer record of Himalayan field experience than myself, and who were therefore more qualified for this publication. On the other hand it was most tempting to apply my experience gained in other mountain ranges to a synthesis of the Himalayas. In particular the Andes, the Middle East ranges and the Alps, where the geology is at present in an effervescence comparable only to the days when the large nappes were discovered, form a most fascinating background for the Himalayan studies.

I know only three regions of the Himalayan mountain chain from personal experience; the Central Himalayas with some parts of southern Tibet, the Darjeeling area and, from recent investigations, the Bhutan section of the eastern Himalayas. For evident reasons these two sections will receive a more detailed description. Published and some unpublished information will form the background for the discussion of the rest of the range, to which aim I have consulted most of the pertinent publications on the subject.

It was only towards the end of 1962 that final arrangements to prepare this book were made and a time limit set in order to have the publication ready for the International Geological Congress in New Delhi late in 1964. Unfortunately within the short available interval my other duties have given me little time to devote myself fully to the Himalayan studies. Many shortcomings and mistakes could have been avoided had more time been available, but delay of publication was judged undesirable in view of the expected and hoped-for new material on the Himalayas to be heard at the Delhi Congress. Under these circumstances I can only ask the reader to be lenient and accept my apologies.

Acknowledgments

I am indebted to L. Ulbo de Sitter for suggesting me this fascinating study object. Much of the new, hitherto unpublished information on Bhutan, was gathered during an expedition in 1963, sponsored by the Swiss Foundation of Alpine Research and financed by the Swiss National Science Foundation. The great assistance received by these two institutions is highly appreciated. Special thanks are due to the Government of Bhutan and particularly to the Royal Family, who's invaluable assistance contributed substantially to the success of the journey. Most valuable work

was done by my students Rudolf Hänny, who assisted me during the Bhutan expedition and helped to prepare the geological map, and Geoffrey David Franks, to whom fell the hard task of typing the manuscript, preparing the reference list and assisting me in proofreading. In the preliminary determination of the mostly badly preserved fossils from Bhutan some colleagues were most helpful: Rudolf Trümpy and Bernhard Ziegler for the mesozoic fauna, Helmut Flügel for paleozoic corals, Hans Hess for crinoids and Wolfgang Leupold and Ernst Gasche for calcareous algae. Thanks are also due to Peter Siegner for his potassium/argon age determinations on crystalline rocks from Bhutan.

The greater part of the manuscript was read by Ernst Lehner, to whom I am most indebted. His constructive criticism based on his own Himalayan experience was most helpful.

The efficient editing of the Staff of John Wiley & Sons Ltd., as well as the excellent cooperation of the printer Orell Füssli, was greatly appreciated.

A. Gansser

CONTENTS

INTRODUCTION

Since Burrard and Hayden's Geological map of the Himalayas, published nearly 60 years ago and revised in 1934, no new geological map covering this range has been published. It was therefore desirable to prepare a geological compilation map of the whole Himalayas, incorporating the Karakorum and the Salt Range, as well as a tectonic interpretation of the adjacent region. These maps, which actually form the *pièce de résistance* of the present work, are based on very varying information, and not all the newest results were available. On the other hand regional mapping in the Himalayas has not progressed much in recent years since a great part of the geological effort had to be placed on the economic side, and unfortunately the Himalayas, like many other high mountain ranges, are a rather uneconomic proposition. Just as in the European Alps the mineral wealth is too poorly concentrated to justify economic exploitation. It is therefore hoped that only few of the important local maps have been omitted from this compilation, where in any case the adopted scale of 1 : 2 000 000 precludes the rendering of details. The original geological map of the Himalayas has been drawn on a scale of 1 : 1 000 000. For a uniform topographical base the American Aeronautical Sheets 1 : 1 000 000 have been chosen since they incorporate all the newer topographical informations and form a more generalized topographical background. Because the aeronautical maps covering the mountains are based mostly on the Indian Quarter Inch maps the information of the higher mountain zones is often higly inaccurate. This is also true for the adjoining Tibetan areas. The northern boundaries of India and Pakistan have been drawn as they were shown prior to 1960.

In the text I have tried to replace as much as possible lengthy descriptions by adequate text figures, photographs and profiles, which frequently render the facts more clearly. Practically all sketches, from nature, from photographs or other sources have been drawn of redrawn by myself in order to arrive at a uniform presentation.

Some difficulties arose in the presentation of the facts; should a stratigraphical description of the whole range be followed by tectonic and more regional discussions, or should a more geographical subdivision guide the geological description? Both ways have their merits. Certain stratigraphic units are surprisingly constant throughout the 2400 km length of the range. Other deposits change rapidly or occur only locally and wider correlations are wanting. Major geological units based on regional basins of deposition (geosynclinal types) can be visualized, but they are not yet sufficiently outlined to be traced over larger areas. Too much generalization along these lines and forceful correlation with the better known Alps has hampered progress.

In order to do justice to the scanty geological knowledge of a very large mountain chain I propose to subdivide the Himalayas (including

the Karakorum) into geographically framed sections and stress in each the items of special interest. This will sometimes lead to unavoidable repetitions of subjects, but it is felt that this procedure can be better followed by the reader less acquainted with Himalayan geology.

Preceding the description of the Himalayas proper some introductory remarks on their general setting will be necessary. Then follows a discussion of the northern shield elements of India which border the Gangetic foreland of the Himalayan range and which, being actually incorporated in the mountains, play an important role in its older stratigraphic and tectonic history. In a concluding chapter the Himalayas and their regional framework are discussed in the light of geological facts and deductions arrived at in the more detailed descriptions.

A general introductory historical chapter is deliberately omitted. The large number of scientists engaged in Himalayan research would alone demand a lengthy treatise, and this is not within the scope of the present work. Pertinent items will, however, be briefly mentioned in each section.

For the present work I propose the following main heading:

WIDER FRAME OF THE HIMALAYAS

The regional setting of the Himalayas is preliminarily discussed in order to facilitate certain comparisons which may be necessary during the more detailed description. In a concluding chapter I shall again stress some regional aspects of special interest.

I. Western, eastern and northern areas

II. Northern border of the Indian shield Mass

Shield elements of Peninsular India border the Himalayas to the south and were actually involved during its mountain building cycles. A somewhat more detailed description for comparative purpose is therefore warranted.

HIMALAYAS INCLUDING THE SALT RANGE AND THE KARAKORUM

After Burrard and Hayden (1934) and Bordet (1961) the Himalayan chain can be subdivided into the following regional geological and geographical units (Fig. 1):

III. Salt Range

As an intermediate structure between the Indian shield and the Himalayan chain it will be discussed first, following the chapter on the northern shield elements.

IV. Karakorum

This imposing mountain range, over 400 km long borders the western Himalayas to the north and forms a connection to the Pamirs, and thus to the Central Asiatic ranges.

V. Punjab Himalayas

This 550 km long section of the true Himalayan chain is bordered in the west by the Indus River and in the east by the Sutlej River. It includes Kashmir and the Spiti region, geologically the best known area of the Himalayas.

VI. Kumaon Himalayas

From the Sutlej eastwards this section stretches 320 km to the Kali River on the western boundary of Nepal. It includes the Garhwal Himalayas and parts of southern Tibet.

VII. Nepal Himalayas

From the Kali River in the west to the Tista River in the east these extend along the whole 800 km length of Nepal.

VIII. Sikkim / Bhutan Himalayas

This part of the Himalayan range is occupied by Sikkim and the independant state of Bhutan and measures about 400 km.

IX. NEFA Himalayas

This eastern part of the range (400 km long) leads from the eastern boundary of Bhutan to the crossgorges of the Tsangpo-Brahmaputra. Lying in the somewhat politically unsettled North Eastern Frontier Agency (NEFA) it is the geologically least-known part of the whole Himalayan range (former Assam Himalayas).

Each section of the Himalayan range will, where feasible, be subdivided into:

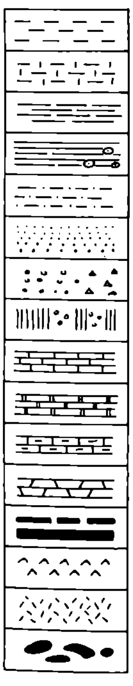
1. Sub-Himalayas
2. Lower Himalayas
3. Higher Himalayas
4. Tibetan Himalayas (Tethys Himalayas)

and discussed in this sequence.

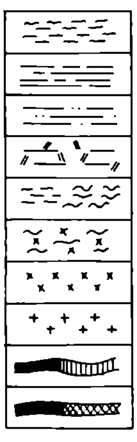
CONCLUSIONS

Here the foregoing facts are discussed regionally. We subdivide this final part into the following chapters: A, Geologic history of the Himalayas; B, the regional structural outline of the Himalayas; and finally, C, the regional setting whereby we draw special attention to the general tectonic map covering a large part of south central Asia.

Generalized lithological legend and abbreviations used on maps, sections and text illustrations



	sediments
Cl	clays
M	marls
Sh	shales
Sl	slates (with concretions)
s Cl	sandy—silty clays
Sst < f / crs	sandstones < fine / coarse Qz quartzites
Cgl Bc	conglomerates, breccias
Tf Ag	tuffs, agglomerates
Lst	limestones, marbles
Dol	dolomites
cl—sh Lst	clayey—shaly limestones
Ch	cherts
C	carbonaceous shales, coals. (Fe horizons)
Gy	gypsum, anhydrites
St	rock salt
Ex	exotic blocks



	metamorphics and igneous
Phl	phyllites
Sch	schists
Sch	garnet schists
Sch	schists with biotite porphyroblasts
Sch—Gn	schistose gneiss—gneiss
Gr Gn	granitic gneisses
Gr	granites—diorites Pgt pegmatites
Pf	porphyries and porphyrites
A	amphibolites, basic rocks i. g.
U	ultrabasics (peridotites, serpentines)

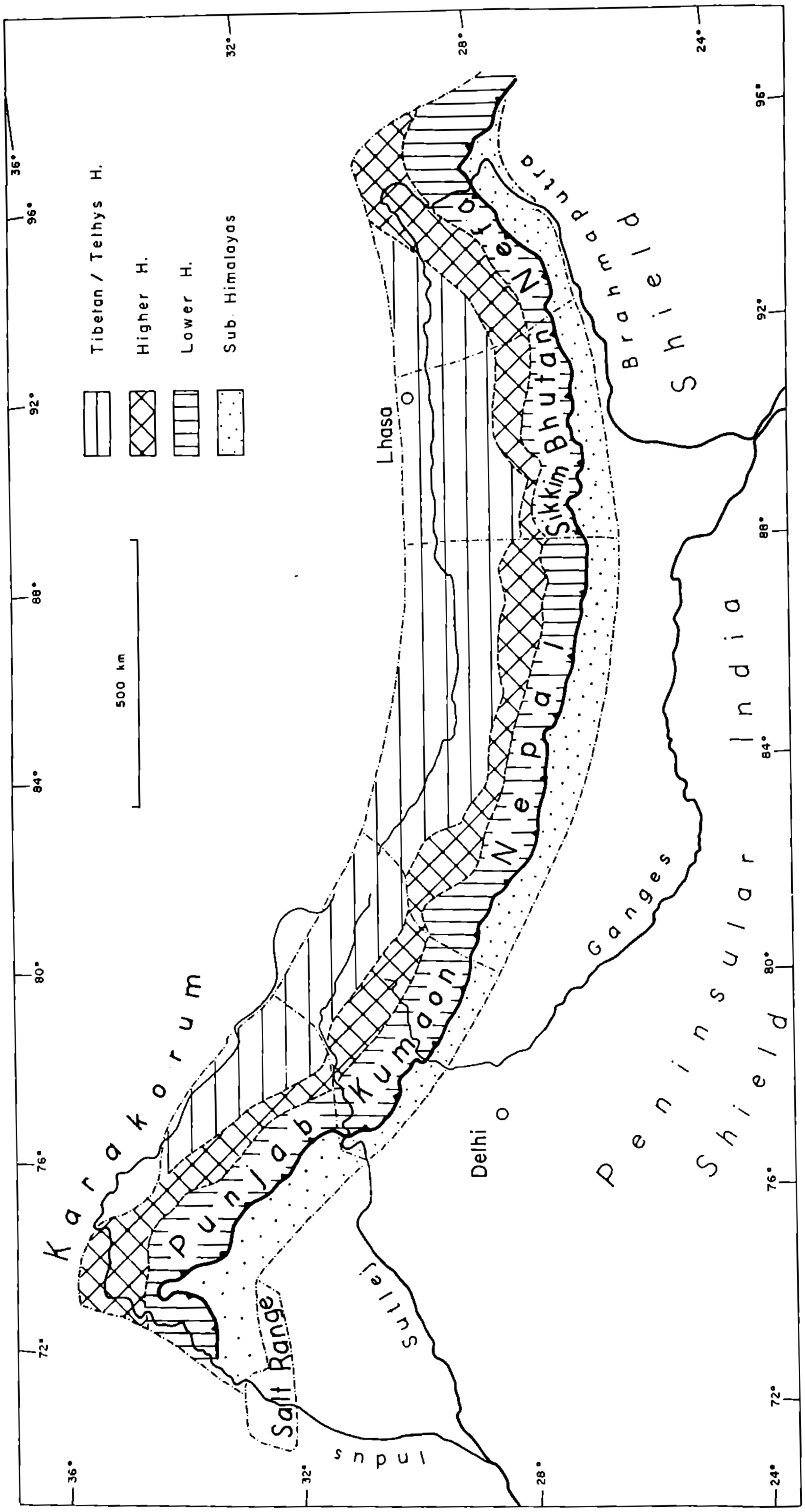


Fig. 1 *The general subdivisions in the Himalayas followed in the text*

THE WIDER FRAME OF THE HIMALAYAS

CHAPTER I

WESTERN, EASTERN AND NORTHERN AREAS

In the central part of Eurasia, just above the northwards-directed spur of the Indian shield, we find the world's largest concentration of mountain ranges, the Pamirs. These mountains are situated on the western side of the Tibetan high plateau, which in itself is the largest mass concentration of our globe's surface. From the Pamirs some of the world's largest mountain ranges branch off to the west and to the east, a fact well visible even on the most general topographical map of Eurasia.

The Himalayas follow south of the Pamir mass and, bordering the Tibetan plateau to the south, form the southernmost Asiatic high range. They end in the west and east in remarkable syntaxial bends. The spectacular mountain ranges are thrust against the Indian shield, or rather underthrust by the latter. The thrust sheet tectonics of the Himalayas are related to this very fact, and are lacking in the same magnitude in all other Asiatic mountain ranges.

The mountain ranges west and east of the Pamir knot are different from each other. The eastern ranges are larger, have parallel structures and are more uniform in their composition. Intervening wide stable basins alternate with well differentiated adjacent orogenic belts.

The western ranges show the characteristic one-sided virgation, a feature clearly visible as far as Central Iran. This structure is so remarkable that the author has called them *sheaf ranges*, whereby only one side of the sheaf is produced. The virgations are uniformly open towards the west, that means away from the Pamirs. The virgation of each range opens into a pseudobasin; these are themselves unstable and generally strongly deformed. The northern limit of such a *sheafing* range is formed by steep faulting, mostly shear faulting, but more rarely thrusting. This fact is clearly visible on Pl. I B. It is very difficult to find an explanation for this type of structure. It seems to be related to a widening of the orogenic belts between *Scharungen* caused by advancing shield elements. In the mountain chains west of the Pamirs we recognize that sheaf ranges are developed between the northwards-protruding Indian shield (Punjab area) and the northern spur of the Arabian shield (northern Syria). Towards these two shield spurs the sheaf structures disappear and more normal ranges set in (Zagros ranges bordering the Arabian shield).

Few general geological maps show the complete geological picture clearly; the earliest was ARGAND's sweeping synthesis in his *Carte tectonique de l'Eurasie* (1922). The Russian compilation map of Eurasia (1956) gives the status of about 10 years ago, but does not show the Central Karakorum and its important continuation in the Hindu-Kush ranges of Afghanistan. The most recent regional publication is the Tectonic Map of Asia (1963) prepared in Russia. The subdivision of this map, based on folding phases and type of geosyncline, is still most uncertain in many regions, and it does not cover the Himalayas and surrounding areas. Some new information on the Afghanistan ranges can be gathered from the Geological and the Oil and Natural Gas Maps of Asia and the Far East, prepared by the United Nations Economic Commission for Asia and the Far East (1959 and 1962). In the following we refer to the Tectonic Map (Pl. I B), which was prepared from all the available information and interpreted with the author's own ideas, and which presents the Himalayan range in its regional setting.

This regional picture shows that the southern shield elements such as the Indian and Arabian shields have actively deformed the Alpine belt and seem responsible for the outline of the orogenic ranges. This northwards movement was probably not contested by a southward movement of the northern Fenno-Sarmatian-Angara (stable) mass. The spectacular Himalayan syntaxis can hardly be explained in a different way. We will deal with this stimulating problem in a final chapter and restrict the present discussion to a very general survey of the wider frame of the Himalayan range.

TIEN-SHAN

North and east of the Pamirs, we find one of the largest mountain ranges of Asia in the Tien-Shan,

3000 km long and up to 600 km wide. In the east a system of parallel, low, and relic ranges disappears in the Gobi Desert. But west of Urumchi the Tien-Shan has its full height with deep contrasting depressions; a contrast such as that between the 6500 m high Bogdo Ola Range and the 700 km long Tien-Shan *graben* with more than 200 m below sea level (Turfan). The old Tarim mass causes the northwards bulge of the Tien-Shan and the narrowing of the middle part of the range. Here we have the highest elevation, the 7200 m high Khan Tengri. North of the Pamir nucleus, the southwestern Tien-Shan continues in the Alai Range and further west the ranges, so far parallel, spread out. Here we note the striking contrast of the structural alignments east and west of the Pamir centre, i. e. the eastern parallel ranges and the western pronounced virgations. As a westernmost continuation of the Alai, the Karatau trends towards the southernmost Ural chain, and it is still a disputed question whether or not a connection with the N-S striking Urals does exist or if the Ust-Urt mass of the Aralsk Sea intervenes. Southwards from the Alai-Karatau, successive ranges branch off and turn through west into a southwards trend. This fact is particularly well expressed in the Fergana depression, a classic area for sheaf ranges.

The *structural* backbone of the Tien-Shan is old, and to a large extent probably Precambrian. Leuchs (1937) stresses the importance of the Hercynian orogeny, but in my opinion the evidence for strong Hercynian orogenic movements is rather questionable, though pre-Carboniferous epeirogenic adjustments have certainly played an important role. Above the Precambrian metamorphics, tillites originating from late Precambrian or early Cambrian glaciation of the Tarim Basin are widespread in the southeastern Tien-Shan (Norin, 1937, 1941). The marine transgression begins with the Upper Cambrian and Silurian. Marine Devonian and Carboniferous reflect epeirogenic movements with local overlaps but show no sign of real orogenic phases. With the Upper Carboniferous and Permian a general regression sets in, leading to the widespread continental Angara deposits with their world-famous development of reptiles in the Permo-Triassic. Continental deposits with evaporitic intercalations reach into the Upper Cretaceous, and in some areas include the Tertiaries (Hanhai deposits). In the eastern Tien-Shan important late Jurassic orogenies are followed by transgressive Cretaceous. Marine Cretaceous transgressions begin also in the western Tien-Shan in the Fergana Valley and continue eastwards, along the southern Tien-Shan border, where they gradually become younger. Norin found important orogenic movements along the southern Tien-Shan, directed against the Tarim mass. Thrusts of alpine age are reported, but otherwise the Alpine phase affected the Tien-Shan mostly as morphogenetic disturbances of great magnitude, and led to the present elevations and consequent glaciation. How far the Alpine orogenies of the southern Tien-Shan have actually affected the main range is difficult to decide. The Tien-Shan graben, not unlike the Rocky Mountain trench, divides the southern, intensely folded and more metamorphic Tien-Shan with granite intrusions, from the more monotonous northern Tien-Shan with its thick deposits of Middle Palaeozoic rocks (Bohlin and Norin, 1960).

Precambrian orogenies are responsible to a great extent for the structures of the present Tien-Shan and subsequent disturbances, mostly epeirogenic, are aligned on the old structural trends. This conformity of older and younger structural trends may suggest that the influence of certain phases, as for instance the Hercynian, has, in my opinion, been greatly exagerated.

TARIM BASIN

East of the Pamirs, the Tien-Shan borders against the Tarim Basin with a sharp thrust contact. This depressed basin is an old stable mass which has been little altered during the geological history of Central Asia, but has played an important role in the alignment of the surrounding mountain ranges. The northern and northeastern border zone has been investigated by Norin (1937), (Bohlin and Norin, 1960). Just as in the southern Tien-Shan, a Precambrian crystalline basement is transgressed by little-disturbed and surprisingly little-metamorphosed late Precambrian sediments, partly of glacial origin with thick varval deposits. They have been unconformably overlain by marine Upper Cambrian. From the Carboniferous to the present day the Tarim Basin has been subsiding, and was filled with the outwash of the Angara continent, and then by Hanhai and Quaternary deposits. Under recent gravels and sands are extensive lagunal clays, suggesting large Quaternary lakes. The question of a regional dessication of this Central Asian region is still disputed. Leuchs (1937) attributes the drying of the end-lakes to a shifting of the feeding channels by drifted sand and possibly to young tectonic deformation rather than to a regional dessication. A decrease in lake surface levels, as witnessed by many widespread ancient lake terrace levels is however widely accepted for most parts of Central Asia.

KUN-LUN RANGE

South of the Tarim Basin, and forming the north border of the Tibetan high plateau, follows the

Kun-Lun Range. It is connected to the Pamirs by the *Mustagh-Ata Range,* striking NNW. It merges into the Alai ranges north of the Pamirs and closes the Tarim Basin towards the west. This northerly strike direction seems still a reflection of the western Himalayan syntaxis which causes the northwards bulge of the Pamir ranges. Eastwards the Kun-Lun divides into a northern branch, the *Astin-Dagh*, which continues into the *Nan-Shan* and ends before reaching the Kuku-Nor, and the *southern Kun-Lun* on the opposite side of the *Tsaidam Basin.*

Up to the Angara regression, with Jurassic coals and plant remains, the geological history of the Kun-Lun is not unlike that of the Tien-Shan, although the presence of ultrabasic rocks may indicate a more deep-seated orogeny. The fact that the Kun-Lun forms an important divide between the Angara sedimentation in the north and a corresponding marine influence in the south (Tibet) may also indicate a more orogenic belt. During the Precambrian there must have been several important orogenies; some disturbances followed in pre-Devonian times and a marked orogeny at the end of the Angara sedimentation took place prior to the Cretaceous transgression. We will see that this late Jurassic to earliest Cretaceous orogeny is most pronounced in the ranges west of the Pamirs.

The northeastern branch of the Kun-Lun, the *Astin-Dagh* and *Nan-Shan,* has more a block mountain range character, and differs from the main structural style of the Kun-Lun. Young Tertiary sediments, mostly fine clastics up to 4000 m thick, are intercalated between the block-like remnants of the older range. The *Tsaidam Basin* to the south is geologically very similar to the Tarim Basin. The division between the Astin-Dagh and Nan-Shan is young and the uplift of the impressive horsts and blocks of these ranges occured in the Mio-Pliocene. At the same time the subsiding Tsaidam Basin was filled with young sediments and only in the Plio-Pleistocene was the basin uplifted to its average height of 3000 m (Bohlin and Norin, 1960).

HIGH TIBETAN PLATEAU

The southern and main Kun-Lun borders the *High Tibetan Plateau* to the north. We owe much of the available geological information on the central part of Tibet to Sven Hedin's expeditions, but wide areas are geologically still largely or even totally unknown. The geology of Central Tibet is not complicated, with elongated ranges striking mainly E-W. Marine Jurassic is followed by some Cretaceous and widespread, mostly continental, Tertiary formations. The wide distribution of young volcanic rocks in the Tibetan plateau and along the Kun-Lun Range is curious and little-understood. They have been observed by Sven Hedin in the Transhimalayas (Hennig 1916). Very young basaltic lavas together with relic volcanic cones are variously reported, suggesting a very young, probably Pleistocene, age. Indications in the southern Kun-Lun suggest even post-Pleistocene vulcanism (Leuchs, 1937).

Westwards the highland pinches out between the Karakorum in the southwest and the Kun-Lun in the north. Here, on the eastern side of the Pamirs, Angara sediments extend further to the south, interfingering with the Tethys-type marine formations which are widespread in Inner Tibet.

Eastwards the Tibetan high plateau is affected by the eastern Himalayan syntaxis. Its northeast border lies along the Nan-Shan ranges, which end in the Kuku-Nor depression where the NNE striking Huangho ranges set in, already influenced by the Ordos mass. The only E-W striking element is the Tsinling-Shan Range, which with its metamorphism and basic rocks forms a major structural element.

Only in Northeast and East Tibet are older formations known, which may give some indication of the deeper configuration of the Tibetan platform. From the Tang La Range on the border of Tibet and NW Yunnan, Huang (1960) mentions Devonian formations and suggests a Hercynian core for the range. Similarly he reports thick Devonian and Carboniferous deposits from the Lhasa-Bomi folded belt with intercalated submarine volcanics representing the deeper elements of the Tibetan platform. This platform ends in the Chamdo region (eastern Tibet) where the Chamdo fold belt contains geosynclinal deposits of Lower Palaeozoic, with probably an unconformable Permo-Carboniferous cover (Huang 1960). It is still questionable whether or not the Tibetan plateau is actually a Hercynian consolidated *Grundgebirge* as suggested by Huang. In western Yunnan the general trend swings southwards into the Burmese ranges around the eastern Himalayan syntaxis, and is bordered to the east by the large and complex stable depressions of Szechuan and South China.

The influence of the Himalayas is already seen in southern Tibet where the Transhimalayas (Kailas Range), a continuation of the Karakorum and Ladakh ranges to the southeast, represent a structural element lying south of the Pamir nucleus.

THE PAMIRS

This most pronounced mountain nucleus has stimulated geological interest since its first investigations nearly 100 years ago, and has lately been thoroughly explored by Russian expeditions.

Some results are compiled in the 1:2,500,000 map of Russia. The investigations up to 1934 have been reviewed by GUNDLACH (1934), (see also NALIVKIN, 1960). The importance of the Pamirs as a major mountain *Scharung* in Asia is well known. This knot-like form is to a great extent the result of the northwards drive of the northwest Indian shield spur which also caused the western Himalayan syntaxis. Its influence on the Pamirs is seen in the northwards bulge of its major elements.

From north to south we can distinguish a northern sedimentary belt, a central crystalline belt, a southern sedimentary zone, and the southern crystalline belt in the Karakorum. Alpine orogenies become increasingly manifest in the Pamirs from the north to the south, the structural alignment remaining roughly constant throughout. The subdivisions into the above mentioned belts, however, oversimplify the geological aspects of the Pamirs. Being actually a *Scharung* of various large mountain ranges, the structures are generally much more complex.

No sharp boundary can be traced between the Alai Range, which is the western continuation of the Tien-Shan, and the northern Pamirs. The thrust zone of Kashgar (south of the western Tien-Shan) continues westwards but the sedimentary facies is transitional from Alai to the northern Pamirs. The Angara influence is still felt in the northern Pamirs, while in the southern sedimentary zone marine sediments replace most of the Angara beds and a continental influence is seen only in the Lower Cretaceous. The predominantly Jurassic Pamir limestones are widely distributed. Upper Cretaceous deposits are again marine and transgressive, similar to the main transgression in the Fergana depression. The intermediate crystalline (the central crystalline belt) is steeply folded and is thrust northwards over the sedimentary zone. Thrusting is Alpine, but the folding of the crystalline is reported to be Hercynian, though it may, in accordance with other regional observations, belong to a much older phase. The widespread assumption of Hercynian activity must by carefully analyzed. Along the southern border the thrusts are south directed and dip steeply to the north. In the central part of the middle crystalline belt some north-south-directed fault zones occur, and may be related to the general culmination. The Fedtshenco Glacier follows one of these fault zones, its 77 km length making it the world's largest extrapolar ice-stream. The southern crystalline belt belongs geologically to the Karakorum and will be discussed more fully in the respective section.

Westwards the Pamir *Scharung* opens out into a broad virgation. As already mentioned this is in strong contrast to the eastern ranges with their parallel structures. We have already noted how the western extension of the Tien-Shan-Alai virgates in the Fergana region by forming westward and southward diverging branches from the Karatau. In the western extension of the northern Pamir-Alai ranges the Fergana-type structure is repeated in a surprisingly similar way, the virgation extending into northern Afghanistan. The predominantly sedimentary zones cross the Oxus River (Amu Darya) between its northern bulge at Badakshan in the east and Termez in the west in separate, well-outlined ranges, while the crystalline zones enter northernmost Badakshan. These ranges strike and abut with a steep angle, against the *Hindu-Kush*, the western continuation of the *Karakorum*.

The connection of the north-south-striking western Pamir elements with the NE-SW-striking Hindu-Kush is still little understood and much work remains to be done in this northern part of Afghanistan. Recently DESIO and co-workers have investigated the central Badakshan region and published a preliminary account (DESIO et al, 1963). It is hoped that in connection with his previous investigations in the Hindu-Kush, a more comprehensive picture can be given of this fascinating region.

PAMIR – HINDU-KUSH ELEMENTS IN AFGHANISTAN

Some of the following information is based on my own rapid traverses through Afghanistan guided by J. P. HUNGER from the Afghan Geological Survey, while the remarks on the adjoining areas are based on the new compilation map of Iran (supervised by the author, 1959) and on earlier and more recent personal reconnaissance work in this country. The *Hindu-Kush* in Afghanistan fans gradually out towards the west from a NNE-SSW direction into an ENE-WSW strike. Its northern branch separates the gently folded Mesozoic and predominant Tertiary sediments of northern Afghanistan (the last remnant of the Pamir-Tien-Shan ranges) from a much more complicated sequence of metamorphics, with marbles and intrusions of granodiorites which form the core of the Hindu-Kush. Transgressive Permo-Triassic is found here, together with local remnants of older Palaeozoic rocks in the Kabul region. The wild mountain country of Nuristan, northeast of Kabul, consists mainly of gneisses, schists and granite intrusions with complicated migmatite zones. Pegmatite dykes are frequent, some famous for very large beryllium crystals. This crystalline zone, belonging to a southeastern branch of the Hindu-Kush, crosses the Kabul region and can be followed into the region of Kandahar, though here much reduced and covered by younger sediments. Between this southern

branch and the main branch, continuing north of Kabul towards Herat in the west, we recognize a virgation of mountain ranges which gradually plunge into the Helmand River basin. These ranges are not simply built, for they often contain crystalline cores and remnants of Palaeozoic sediments below a widespread transgressive Mesozoic cover.

North of Kabul, where the two Hindu-Kush branches join, a tectonic zone of major importance can be noted. This zone is well exposed in the Panj-Shir Valley and continues westwards over the Shibar Pass. The importance of this tectonic trend is underlined by boudinaged ultrabasic rocks with irregular ferruginous limestone and dolomite lenses in black slates not unlike the Pasu slates of the Karakorum. On both sides of this tectonized zone follow schists, gneisses, migmatites and fully granitized sections, with boudins of banded amphibolite. The northern crystalline zone contains large marble intercalations strikingly similar to the marble zones of the Karakorum.

The *southern border of the Hindu-Kush crystalline core* is again an important tectonic line, well exposed in the Kabul River gorge east of Kabul. Here the Hindu-Kush gneisses, profusely criss-crossed by granitic dykes and amphibolites, are thrust southwards over steeply dipping black schists with radiolarites, Flysch-type shales and large peridotite lenses. This Flysch zone with ultrabasic rocks contains a wild mixture of blocks of various kinds, well exposed south of Kabul just north of the Gardez Lower Tertiary Flysch zone. It is indistinguishable from similar olistostrome-type deposits of Iranian Baluchistan, which I have called *coloured melange* (GANSSER, 1955, 1959). There is little doubt that the coloured melange, with its associated ultrabasic rocks belongs to highly disturbed *ophiolitic belts* and thus marks zones of structural importance. The still problematic block regions in the northern Central Himalayas recall this coloured melange and will be discussed in a special section (page 123). We may here anticipate that they belong to the important structural division between the Himalayas and the Kailas Range, which is marked by ophiolites and which again would correspond to the tectonic separation between Himalayas and Karakorum. Thus, it could be suggested that the coloured melange zone south or southeast of the Hindu-Kush Range would correspond to this same first-order tectonic zone. Unfortunately, the connection between the southern limit of the Afghan Hindu-Kush and the southern border of the Karakorum is still shrouded in geological mist (for tentative connection see Pl. I B).

Only the *northern branch of the Hindu-Kush* continues westwards. In the region of Herat, near the Persian border, the important tectonic northern edge of the crystalline rocks is well exposed, but so far is known only from rough reconnaissance. I was impressed by the extreme tectonization of the augen gneisses with marble intercalations and cross-cutting aplitic dykes. They dip steeply to the north and are transgressed by Tertiary clastics. Remarkable are the enormous crystalline breccias forming the base of the Tertiary sequence, and consisting of large (2-5 m diameter), unsorted boulders of gneisses, aplites and amphibolites in a matrix of green silts. They appear to be over 500 m thick. Even 1000 m higher up, in the Tertiary section of red and green silts and sandstones, there are sudden intercalations of boulder breccias with components measuring 5 m. This peculiar sedimentation recalls large fanglomerates of a catastrophic type.

PAMIR — HINDU-KUSH ELEMENTS IN IRAN

Further westwards the Afghan Hindu-Kush continues into Iran and forms the southern branch of the *eastern Elburz chain*, south of the Binalud uplift of Meshed with its crystalline core. The large serpentine masses of Sabzavar further west indicate again a major tectonic line and recall the northern border of the Hindu-Kush. Here we recognize, however, a regeneration of the mountain ranges north of the Hindu-Kush that we noted in northern Afghanistan. These ranges become greatly depressed towards northwestern Afghanistan, where they are only very little folded. Only after crossing the Iranian border do they rise again to the impressive uplift of the Binalud at Meshed and to a large northern branch, with Jura-type folding in the Mesozoic and Palaeozoic, which continues into the *Kopet Dagh*, the border range with Russia. The Kopet Dagh is again a range with a classic westwards virgation of the sheaf type, plunging into the Gorgan depression and the southern Caspian Sea. The structural feature of the Fergana region and of North Afghanistan is here repeated in every detail. Steep faulting and flexuring along the northern Kopet Dagh are responsible for its extremely straight alignment. The southern branch of the Kopet Dagh-Gorgan virgation continues as the main *Elburz Range*. This would mean that the Elburz corresponds to the mountain ranges north of the Hindu-Kush alignment, and could thus be compared with the Pamirs. It may be interesting in this connection to recall that the Elburz as well as many of the highly complicated ranges in Central Iran are characterized by 3000 m of plant-bearing Lower Jurassic, a facies reminiscent of the Angara-type deposits which are still widespread in the northern Pamir ranges.

EASTERN AND WESTERN CONTINUATION OF THE HIMALAYAS

After having followed the Karakorum via the Hindu-Kush into the Iranian ranges, we may deal with the eastward and westward continuation of the actual Himalayan range. We have already noticed that the Himalayas terminate in both directions, east and west, in most spectacular syntaxial bends, caused by the northward-directed spurs of the Indian shield. Around both bends, the Himalayan ranges continue into a complicated system of southward-running ranges. In the east we recognize the Burmese ranges; in the west the Salt Range and the Hazara ranges are followed by the peculiar Sulaiman arch and the Baluchistan chains. Both syntaxial bends of the Himalayas and their nearer surroundings will be dealt with in more detail in later chapters. While much is known about the *western syntaxis*, little is yet understood of the *eastern syntaxis* and its structural aspect. The predominantly Tertiary and Upper Cretaceous Burmese ranges (Arakan Yoma), emerging from the Andaman Sea, strike towards the north, and before reaching the Shillong Plateau (an element of the Indian shield) swing to the northeast. They do not turn around the eastern Himalayan syntaxis but are cut off by crystalline thrust masses which continue southwards to join the crystalline masses of the Shan Plateau of Central Burma.

Amongst these Burmese ranges the still highly problematic *Arakan Yoma* is outstanding. Its strongly folded Flysch-type sediments, mostly of Cretaceous age, contain ultrabasic intrusions aligned along an eastern fault zone and present a strong contrast with the rocks of the Sulaiman Range west of peninsular India. A certain similarity with the formations of the Indus Flysch belt limiting the Himalayas to the north is evident, but the latter zone is lost in the northeastern Himalayas and no connection with the Burmese equivalent is visible.

In the *western continuation* we note how the Salt Range west of the Indus is offset by the Sulaiman Range, while the Hazara ranges, which form the western continuation of the main Himalayas west of the syntaxis, continue southwestwards although the whole range diminishes greatly in magnitude. West of the Indus, and just north of the Trans-Indus Salt Range, only a narrow belt is left below the southern branch of the Afghan Hindu-Kush. Ophiolitic rocks are present, marking the border against the meagre Himalayan continuation. On the other hand the *Sulaiman Range* develops into a well-marked system of folds, arching garland-like and joining the southern Baluchistan ranges at Quetta. Already the Trans-Indus Salt Range has produced some garland folding on a smaller scale. Most likely the garland-like syntaxial folds of the Sulaiman Range are caused by basement influence of the Indian shield similar to, but smaller in magnitude than, the Himalayan syntaxis. The *Baluchistan ranges* continue southwards and reach the sea at Karachi. They show a large virgation towards the west, with east-west-directed steeply folded ranges in a Flysch-type Lower Tertiary, running parallel to the Baluchistan coast. Near the border between Pakistan and Iran we note a new, most important virgation. The northern part of the Baluchistan ranges strikes northwards, around the *Helmand basin* of Afghanistan and virgates again westwards into the northern Lut Desert of Iran. The southern ranges continue along the coast westwards and border the old crystalline basin of the Djaz Murian. Extensive masses of coloured melange limit the Flysch sediments against the basin which, on its northern border, has one of the most striking sub-Recent to Recent volcanic landscapes.

This volcanic belt begins in the southernmost Helmand basin in the Kuh-e-Sultan group, and the Taftan volcano is situated in the northward-directed Baluchistan Range. From here to the northwest sub-Recent volcanoes play an important role and are related to major tectonic trends. It is an interesting fact that east and north of the Kuh-e-Sultan volcanic group, *sub-Recent to Recent volcanic activity is unknown.* None is reported from the Tien-Shan, the Pamirs, or the Himalayas, except for the supposed Recent lavas of Tibet and the Kun-Lun. Only in the Middle Burmese ranges is some sub-Recent volcanic activity known from the Popa andesitic volcano and the explosive craters of the lower Chindwin (HUBER and BURRI, 1933). Further to the south the Narcodam and Barren islands (east of the Andamans) are volcanic—the latter was active in the 19th century—and lead into the volcanic belt of the Sunda ranges.

Opposite the Oman Peninsula, the Baluchistan ranges arch northwards and align themselves with a most important rejuvenated N-S-directed tectonic feature, the *Oman line* (GANSSER, 1955). Separated by important strike-slip faults, they adjoin the *Zagros ranges*, which strike northwestwards parallel to the Persian Gulf as a Jura-type fold range with spectacular salt tectonics. This saline belt, most probably of Cambrian age, borders the northern Arabian shield, similar to the Cambrian salt formations of the Salt Range at the northwest border of the Indian shield. The Zagros folds are directly related to this salt belt, quite apart from the equally important Tertiary salt deposits. One may venture to ask, and this question has to be discussed later, how far the sudden frontal thrusting of the Himalayas over the Indian shield, or underthrusting by the latter, is related to a saline belt bordering this shield.

The *northern border of the Zagros* is again an *important tectonic line*, characterized by ophiolitic

rocks and radiolarites. It divides the Alpine Zagros Range from the intricate tectonics of Central Iran, which may reflect elements of the Hindu-Kush and even more northern elements. It is not the place here to discuss further these most intriguing and stimulating correlations. Much new work is going on at present in Central Iran and new discoveries of regional importance are being made. They may eventually add new material to solve our problems.

CHAPTER II

NORTHERN BORDER OF THE INDIAN SHIELD MASS, NORTH PENINSULAR INDIA

The clearest and most impressive border of the Himalayan range is its *southern limit* towards its foreland—the Indian Shield or Peninsular India. The contrast between the alluvial covered lowlands of the Brahmaputra, Ganges and Indus Rivers and the Himalayan range is unique in the world, and the geological difference between the shield, with its northwards-directed grain and the east-west-directed still-active orogeny is equally striking. On the Tectonic map the main geological features of the shield are indicated. They are well known and represented on the geological map of India attached to WADIA's *Geology of India* (1957).

The results of recent geophysical exploration and drilling in the Indus, Ganges, and Brahmaputra basins, bordering Peninsular India to the NW, N and NE, indicate that shield elements can be followed northwards under the southward thrusts of the Himalayas. Furthermore, isolated shield outcrops are known to occur surprisingly near the present Himalayan south front, narrowing the gap of alluvial and Tertiary deposits separating the northern shield elements from the southernmost Molasse-like Siwalik Hills of the Himalayas in some places to only 35 km. As we will further realize, much of what is generally known as the Lower or Lesser Himalayas consists of deposits (mostly pre-Gondwana) which have to be regarded as a normal continuation of the well-known shield rocks in less marginal facies.

The major mountain range of Peninsular India, the *Aravallis*, which incorporates the otherwise undisturbed Vindhyan deposits, strikes with excellently exposed structures at right angles to the Himalayas. Rarely can such a divergence of strike directions of an older and younger mountain range be found elsewhere in the world. Its implication in the later Himalayan structural history is important. Furthermore a large amount of Tertiary sediments, mostly pre-Miocene (pre-Siwaliks) of the Himalayan foreland, have been derived from Peninsular rocks. As we will see later, much of the red clastic Murrees (Oligo-Miocene) have a southern shield origin (Vindhyans) and only with the Mio-Pliocene do Himalayan-derived clastic rocks dominate over sediments derived from the shield. It is for these reasons that a more detailed description of the shield elements will assist us in comparing and evaluating the widespread and still little-understood, mostly unfossiliferous rocks of the southern Lower Himalayas.

In spite of many regional and some detailed investigations which began with the foundation of the Geological Survey of India over 100 years ago, the stratigraphy of the rock formations of Peninsular India is still little known for an area which is generally highly populated and easily accessible. As most of the outcrops consist of Precambrian deposits and igneous and metamorphic rocks fossils are evidently absent. Frequently the outcrops are scattered and continuous sections are rather rare. But even in the younger little-disturbed sediments (the Vindhyans), where traces of fossils have been found and which seem to straddle the important Precambrian-Cambrian boundary, a clear stratigraphical succession is still wanting. The application of modern research has just begun. Age determinations, including combined methods as well as micropalaeontological investigations (spores, coccoliths, etc.), are being introduced but only few results are as yet available (ASWATHANARAYANA, 1956). A promising and most rewarding field of research is still open.

For easy reference, a compiled stratigraphical column of the northern shield elements of Peninsular India is given in Fig. 2. It is based mainly on the results of more recent investigations by HERON (1935, 1953) and AUDEN (1933a) and on various earlier investigations compiled by PASCOE (1950, 1959).

The most important feature of the Precambrian shield rocks of northern Peninsular India is a very marked unconformity separating a tightly folded and strongly metamorphosed assemblage from the overlying formations which in general (the Aravalli ranges excepted) show only minor disturbances and a much lower grade of metamorphism. Rocks below this unconformity have generally

been placed into the *Archaean*, those above into the *Algonkian*, including questionable Cambrian. The regional division into *Dharwars* for the sedimentary representatives of the Archaean, and *Puranas* for the Algonkian rocks is most practical and will be used in the following. In my present account I am mainly concerned with the northern part of Peninsular India, from Rajputana in the west to Bihar in the east, with the addition of the most northwestern (Punjab) and northeastern (Assam) sections of the shield. Rajputana contains the main part of the Aravalli ranges, formed during Purana times, which will be discussed at the end of this chapter.

A regional increase of metamorphism can be noted in most of the older deposits towards the Aravalli Range. Some of it seems temperature related, but on the other hand a certain diaphthoresis indicates later stress influence, probably in connection with the Aravalli orogenies. A sub-

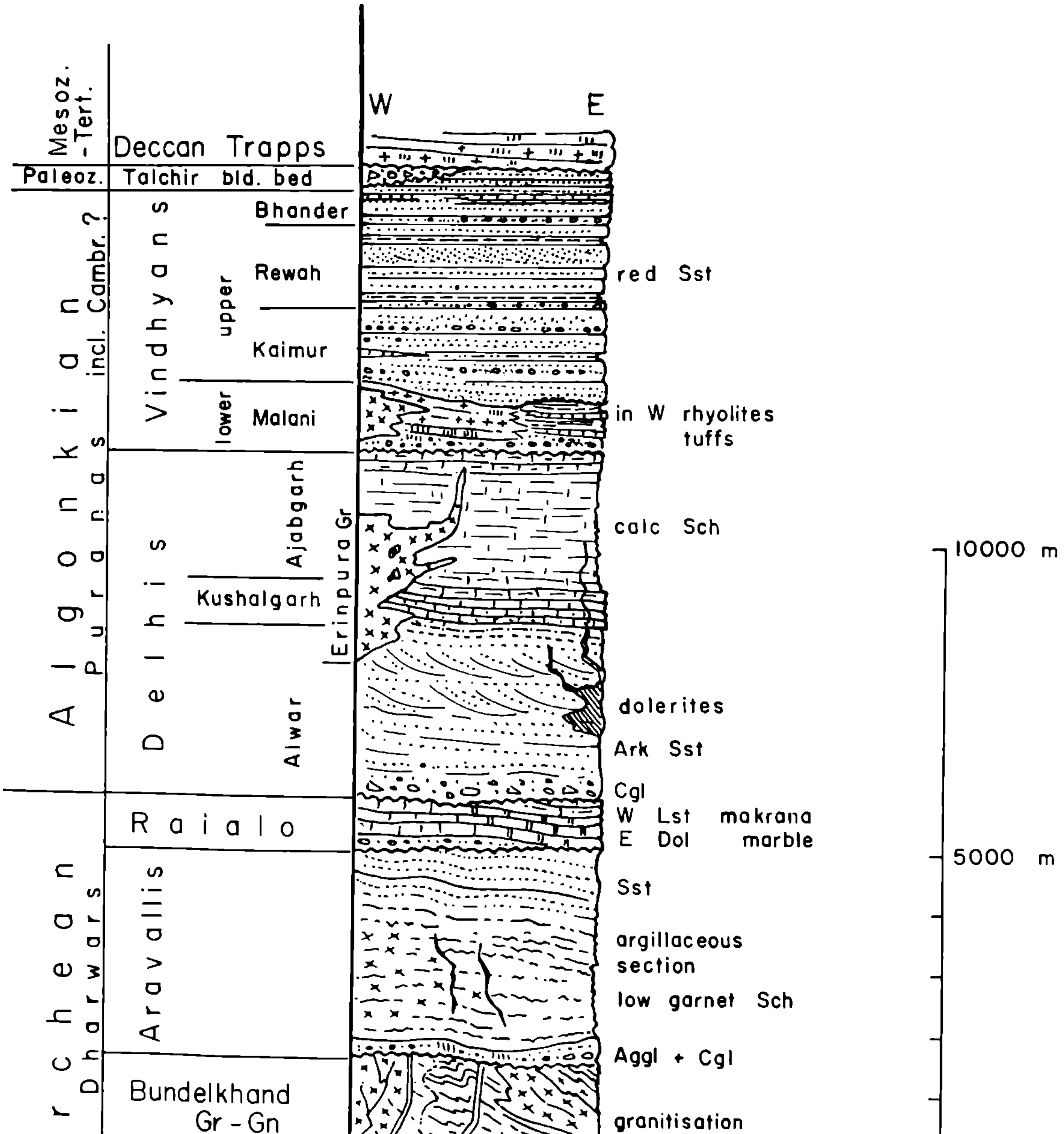


Fig. 2 *Stratigraphy of northern Peninsular India;* compiled after A. M. HERON (1953) and others

division into charnockite-bearing and charnockite-free sections does not apply to the northern part of the shield, though it could be accepted for the southern area. Except for a small occurence in the eastern Mikir Hills of the Shillong uplift (see below) this problematic rock has not so far been recognized in the northern part of Peninsular India.

The northern shield elements can be subdivided as indicated on the accompanying stratigraphical column (Fig. 2).

BANDED GNEISS COMPLEX

The oldest rocks known in the northern part of Peninsular India are the *Banded Gneiss complex* and the *Bundelkhand granites*. But this early date is not universally accepted and recently KRISHNAN (1960) placed the Bundelkhand granites and the Banded Gneiss as post-Aravalli. His Aravalli sediments are correlated with the Dharwars of southern India as the oldest rocks of the Peninsula, a doubtful correlation considering the large unknown tract covered by the Deccan Traps. Unfortunately age determinations of the Bundelkhand granites and Banded Gneisses are not yet available, though a few results from Peninsular rocks are tabulated by Krishnan and will be indicated in the relative section. As long as no convincing evidence exists to change our views we follow the Precambrian stratigraphy as established mainly by HERON (1935).

The *Banded Gneiss*, representing the oldest part of the shield, is the result of a complex geological history (older than 2300 million years), of which practically nothing is known. Strong metamorphism, migmatization and granitization, combined with steeply plunging folds indicate at least one major orogenic cycle, whilst the quartzites and calc-silicates merely hint at pre-existing recrystallized sediments. The excellent parallel banding of the less-disturbed Banded Gneisses is most probably of sedimentary origin. With increasing disturbance an increase in granitization can be noted, leading into nebulous migmatites and finally into inhomogenous local granites. Calc-silicate horizons and quartzites are generally more resistant to granitization than the schists and the former two can be traced in many outcrops for some considerable distance in spite of intricate, often recumbant folds and the tendency to flowage in the fold direction (GHOSH and NAHA, 1962). The original banded rocks consist mostly of biotite-garnet gneisses and schists. Chlorite schists are often present indicating diaphthoresis. Thin quartzitic zones occur and increase in the cores of two domal uplifts of the gneisses to form the oldest, and in these localities probably the least altered deposits. Hornblende schists, thin epidiorites and calc-silicate zones form intercalations in the gneisses and the whole is cut by quartz veins, and pegmatite and aplite dykes distinguishable from younger swarms by their lack of muscovite and tourmaline. Except in local areas with gentle folding the gneisses dip steeply, often vertically, and show a rather constant strike from NNW to SSE, or N-S. This differs from the constant NNE and NE strike of the northern Aravallis, but coincides better with the N-S and NNW trending southern Aravallis below the Chitorghar syntaxis, before the range disappears below the Deccan Traps (see Pl. I B).

The *Bundelkhand granite* has its greatest extension east of the Aravallis in Bundelkhand and covers an area of approximately 30,000 sq. km. Similar granites and granite gneisses outcrop in the middle of the Aravalli ranges and can be followed as small inconsistant outcrops into their northern part.

The main Bundelkhand granite is coarse-grained and consists mainly of red to pinkish orthoclase phenocrysts, some bluish quartz, hornblende, and biotite. Accessories are generally rare. Most of the massive granites show an obscure foliation which seems to be rather constant throughout, its vertical dip and ENE-WSW or NE-SW strike coinciding with the lineaments of the northern Aravallis. Towards the border regions the granites become gneissified and in the southern part there are xenoliths of schists, mostly hornblendic and chloritic, which may represent relics of the banded gneiss sequence if this is older than the granite. Pegmatite veins, usually of smaller size, are frequent. Most conspicuous and characteristic for the Bundelkhand granite are large quartz veins and basic dykes. The quartz veins, measuring 1-40 m in width, run in straight lines, mostly in a NE-SW direction and can stand out as marked ridges up to 200 m above the surrounding country. Such quartz walls can be followed for over 100 km. Dykes of ophitic dolerites, partly altered to ophitic diabases, may be observed running obliquely or at right angles to the quartz walls. They are even more frequent than the quartz veins, of the same magnitude and with approximately the same constancy of strike—predominantly NW-SE. The quartz veins do not enter into the transgressively overlying Aravalli rocks but the later basic dykes, seen to be cross-cutting in a few outcrops, have been regarded as feeders for the sills in the younger Dharwar rocks.

Before the succeeding Aravalli transgression these oldest rocks of Peninsular India were strongly eroded and the earlier structures planed down to a rather gentle land surface. How long this land period lasted is not known, though it was certainly of less importance than the hiatus representing the change from Dharwar to Purana (or *Archaean* to *Algonkian*).

ARAVALLI SYSTEM

Transgressing the older gneisses and granites of the northern shield area we find a thickness of over 3000 m of argillaceous sediments, generally termed the Aravallis. Gritty quartzites, arkoses, or fine conglomerates follow directly over the older granites or gneisses; the arkoses are directly reworked from the underlying granites and the conglomerates are predominantly of angular to rounded quartz pebbles. The basal quartzites are generally thin and may be missing altogether, so that the schistose Aravallis lie directly on the older rocks. Sometimes dirty ferruginous crystalline limestones are interbedded between the quartzites and the higher phyllites which make up the main bulk of the Aravallis. The phyllite group contains argillaceous schists, phyllites, and some shales in the less metamorphic regions in the east which, with increasing metamorphism approaching the Aravalli ranges, pass into biotite-garnet schists sometimes with staurolite and kyanite. The change in metamorphic grade is rather abrupt where the main boundary fault following the SE side of the Aravalli ranges is present. In the high-grade metamorphics NW of this fault zone incipient to more advanced granitization is recognizable. This can lead to local biotite granite masses of intrusive character, with frequent pegmatitic and aplitic dykes similar to the older (pre-Aravalli) dykes in containing no tourmaline and hardly any muscovite.

Some subordinate lenticular limestones and quartzite bands occur amongst the argillaceous sediments, and basic intrusions, mainly in the form of dykes, are frequently met. The latter rocks are dolerites in the unaltered state and amphibolites, hornblende schists, and epidiorites in the more metamorphic zones. Of special interest are ultrabasic rocks, altered to talc schists and serpentines. The combination of thick argillaceous sediments with intercalated basics and ultrabasics may indicate eugeosynclinal conditions for the Aravalli sedimentation, a fact of great importance when considering possible Himalayan equivalents.

East of the Aravalli Range the detritic sediments become coarser and are represented as quartzitic sandstones with intercalated red jasper beds, somewhat reminscent of the overlying Purana rocks but nevertheless grading laterally into the argillaceous facies of the Aravallis.

After the last of the Archaean orogenies and the accompanying granitization of some of the deeper and more disturbed Aravalli sediments came a long period of emergence and erosion during which the certainly substantial mountain ranges were reduced to a low-lying peneplain. This period is believed to have lasted for a longer time than all subsequent periods and marks an important turning point in Precambrian history which is seen in India as the change from the Dharwars to the Puranas (PASCOE, 1950). Only locally has this large hiatus been narrowed down by intervening sediments in the form of the carbonate deposits of the Raialo sequence which is placed by some authors into the uppermost Dharwars, whilst by others it forms the base of the Puranas.

RAIALO SERIES

Beginning locally with conglomeratic quartzites, the Raialos consist in the main of 600-800 m of pure carbonate rocks. They were deposited by an invading sea in local depressions in the northern part of the Archaean surface and thus unconformably transgress the Aravallis, banded gneisses, and granites. Along the SE flank of the Aravalli Range they consist of white pure crystalline dolomites, whilst on the NW flank only calcitic marbles are known. Here the famous *Makrana quarries* have furnished the white marbles, surprisingly similar to the Italian Carrara main marble, that have been used in many of India's famous monuments, notably the Taj Mahal. Limestones or dolomitic marbles are overlain by a thin layer of garnetiferous schists, closing the Raialo sedimentary cycle.

The sudden onset of sedimentation of pure carbonate rocks above the Archaean peneplain is a surprising fact and seems to have its parallel, as we will see later, in the Lower Himalayas.

With the beginning of the *Purana or Algonkian period* orogenic movements in Peninsular India die out, except for those of the Aravalli fold belt. Outside this important mountain range the Purana sediments are little disturbed and only slightly metamorphosed. It will be interesting to note that corresponding Purana rocks of the Lower Himalayas show a surprisingly low metamorphism (Simla Slates) in spite of the subsequent strong orogeny.

Purana sediments were deposited in various basins, often with aberrant alignments. A main land mass divided the southern basins from those of the north, with which we are now concerned, where we distinguish two main sequences, the Delhis below and the Vindhyans above. The latter possibly includes part of the Cambrian just straddling the important Precambrian-Cambrian break.

DELHI SYSTEM

Delhi rocks, corresponding to the widespread Cuddapah of southern India, were for their greater part involved in the folding of the Aravalli Range, and are therefore often strongly disturbed and locally highly metamorphosed.

This may be the reason that there is still some doubt about their inclusion in the otherwise little-altered Purana group. The metamorphism of the Delhis is often highly selective, resulting in variations which, together with the often disconnected outcrops in the separated ridges, makes the recognition of continuous sections difficult. Regionally the metamorphism increases along the main strike direction from the NE towards the SW and consequently the northernmost outcrops which interest us most are of a somewhat lower grade. Here the dips are generally steep and follow the regional Aravalli strike from NNE to SSW, though some deviations do exist. Structures are mostly assymetric with a clear SE vergence indicating movements from the NW, a fact generally recognized for the Aravalli Range (Fig. 3).

The Delhi system can be subdivided into *Alwar quartzites* forming the base, the intermediate *Kushalgarh limestones*, and the overlying *Ajabgarh argillaceous rocks*.

The Alwars consist of 3000-4000 m of quartzites with basal beds of gritty quartzites, arkoses, or conglomerates transgressing onto older rocks with a very marked unconformity. These basal members consist predominantly of locally derived material and when granitic components are present they are often large rounded boulders or pebbles, while the other constituents are mostly angular (a fact frequently observed in transgressive basal conglomerates). The bulk of the Alwar quartzites are pale, mottled, or streaked with brown or reddish tints; they are well cemented (siliceous) and show conchoidal fracturing, the quartz grains interlocking without a trace of original rounding and subsequent secondary growth. Ripple marking and current bedding are frequent. Slightly more micaceous zones underline the bedding, but otherwise intercalations of different sediments are rare. The northernmost Alwar outcrops form the historic ridge of the city of Delhi.

The Kushalgarh limestones follow between the Alwars and the overlying Ajabgarhs and show corresponding transitions on bottom and top. The carbonate rocks (not more than 500 m thick), are finely banded with dark-grey and black limestones. The banding is often accentuated through the limestones' high quartz and mica content which together with the colour, distinguishes them from the Raialo carbonates. When metamorphosed they occur as coarse marbles with large sheaves of grammatite. Most conspicuous are zones of hornstone breccias which may be observed in various horizons of the limestone. They have mostly angular components of fine-grained and light-grey quartzites in a matrix of porcellanitic siliceous slate. This intraformational breccia type appears frequently in various higher Precambrian rocks of the shield, and has its parallel in the Lower Himalayas.

The Ajabgarhs, over 1500 m thick, seem to have been deposited in deeper water than the Alwars. Argillaceous sediments predominate in various stages of metamorphism, since they are more readily affected than their less frequent intercalations of siliceous limestones, ferruginous quartzites, and calcareous slates. Black slates are most widespread, often distinctly banded and with a rusty weathering. Increasing metamorphism can produce black chiastolite schists, biotite schists and in the more calcareous zones calc schists and grammatite marbles. When banded with calcite layers some authors give the name "calc gneisses" to these rocks.

Igneous rocks in the Delhis are widespread. *The intermediate and basic types* are mostly confined to the Alwars as large masses of epidiorites, though some altered contemporary basic lavas have also been recognized. Apart from hornblende schists ultrabasic rocks of the ophiolitic type seem absent; they would be expected rather in the argillaceous Ajabgarhs than in the quartzitic Alwars.

The most important *acid intrusive*, younger in age than the basic rocks, is the widespread *Erinpura granite*. From the largest batholithic intrusion of Mt. Abu in the SW Aravallis many separate lenses can be found northeastwards along the ranges to the north of Alwar City. The main type is a light-grey biotite granite with a varying amount of hornblende. The microcline and orthoclase make up similar proportions and there is a corresponding amount of acid plagioclase which may be locally dominant, forming rather large phenocrysts and giving to the whole rock a more porphyritic aspect. The frequent quartz is of a bluish tint, a striking fact in many Precambrian granites and gneisses. Fluorite is present as a rather frequent accessory. A gneissic banding is often recognized parallel to the general Aravalli strike and in the border zones the granite has been stressed to augen gneiss. Pegmatites, characteristically with large muscovites and tourmalines, occur in the Alwar quartzites as veins, and also as *lit-par-lit* layering within the calc schists of the Ajabgarhs. Granitic intrusions of the Erinpura type are more often observed in the Alwar quartzites than in the argillaceous Ajabgarhs.

Many of the basic rocks have been shown to be syngenetic with the Delhi sediments, while the younger granites intruded into some already severely folded rock sequences. However, as they have been somewhat affected by the latest movements which produced the regional foliation and gneissification, they may be classified as late orogenic, and the intrusion of the Erinpura granites is taken as marking the last part of the strong Aravalli orogeny. These movements of late Delhi times, subsequent to the Delhi sedimentation, gave rise to the largest present-day

mountain range of Peninsular India—the *Aravalli Range*.

Orogenic movements did however continue, or rather were renewed, towards the end of Vindhyan times, since the Vindhyan sequence is strongly folded and faulted along the Aravalli borders. But that the mountain range was already in existance is seen by the influence it exerted on the deposition of the huge mass of arenaceous Vindhyan sediments.

VINDHYAN SYSTEM

The Vindhyan sequence got its name from the Vindhyan Range following the WSW-ENE direction of the Narbada and Son Rivers in the central part of northern Peninsular India. From here to the north the Vindhyan basin extended to the Aravallis in the NW and bordered or partly transgressed the large mass of Bundelkhand granite in the north. Certainly the basin continued northeastwards under the present alluvium of the Ganges Plain, and in the west and southwest a large tract has been covered by the Deccan Trap. The Vindhyans begin with very irregular marine deposits, followed by surprisingly widespread lacustrine, fluviatile and partly terrestrial sediments. This called for a two-fold division into *Lower* and *Upper Vindhyans*. Auden, in his excellent investigation of the Son Valley Vindhyans (1933), proposes a four-fold subdivision, but the constant lithology of his three higher divisions, in contrast to the quite different lowest division, justifies the retention of the older division into Lower and Upper Vindhyans.

The Lower Vindhyans were deposited unconformably over a rather irregular surface, producing a great variety of sediments which can grade into each other both laterally and vertically. The base is characterized by basal conglomerates and quartzites, followed by shales and some lower limestone layers. These are overlain by porcellanitic shales, regarded as lithified tuff horizons, with intercalated trappoid beds. The upper part is a sequence of shale and limestones with some horizons of glauconitic sandstones and grits. Some of the limestones expose irregular cherty bands which in a few horizons form conspicuous round spheroidal features, very characteristic of many Precambrian-Cambrian calcareous deposits throughout the Middle East and Central Himalayas (photos in Auden, 1933). Dolerite dykes are known from the Lower Vindhyans but are missing in the Upper. The average thickness of the Lower Vindhyans does not exceed 1000 m.

The Upper Vindhyans follow with a rather sharp lithological change from calcareous-argillaceous to arenaceous deposits. Considering the large extent and the shallow-water to fluviatile nature of the Upper Vindhyan deposits their lithology is surprisingly constant. Actually they cover a much wider area than the Lower Vindhyans and their original basin of deposition, excluding the Ganges Plain, must have measured at least 180,000 sq. km. They overlie the older rocks unconformably and must have covered the greater part of the Bundelkhand granitic uplift, as may be deduced from the relic patches without intervening Lower Vindhyan deposits. They have, however, never covered the Aravalli Range. Locally an unconformable contact is seen between the Lower and Upper divisions and sometimes this contact is characterized by disharmonic folding, the more easily yielding Lower Vindhyans being thrown into sharp contortions below the thick and undisturbed upper layers.

Three main sandstone cycles can be observed in the Upper Vindhyans, each one preceeded and followed by silty shales. They form prominent scarps and plateau regions, and call for the threefold division of the Upper Vindhyans, from bottom to top the *Kaimur*, *Rewah* and *Bhander*. Most constant are the Kaimur and Bhander, while the Rewah may be locally missing. In all three divisions the *sandstones* are similar, typically finegrained, thin- to thick-bedded (max. 10 m) and in colour predominantly red, with pale reds, pink, and yellowish to deep red. Petrographically the lower sandstones are somewhat more quartzitic and the thick beds of the upper horizons often contain a clay matrix; calcareous cement is practically absent. The predominent quartz grains are usually perfectly rounded, probably of aeolian origin, and frequently show secondary quartz crystallization. Bedding features include very common ripple marks and cross-bedding. As intercalations between the sandstones there occur sandy to silty shales, mostly dark-brown, red, or black and rather carbonaceous and micaceous, with frequent ripple marks and sun cracks. *Conglomerates* are restricted to the Kaimur division, where they contain characteristic red jasper pebbles, probably derived from the Gwalior facies of the Aravallis. *Limestones*, 50-80 m thick, are found in the Bhander division as grey to purple and often rather cherty rocks which contain peculiar concretionary markings regarded by some authors as organic remains. The Upper Vindhyan sandstone, in particular the upper thin-bedded Bhander sandstone with its deep red colour, is used as the most important building stone of India and can be recognized in many of the famous old Mogul monuments.

TRANS-ARAVALLI VINDHYANS

As already mentioned, the Vindhyan basin was bordered on its NW side by the high Aravalli mountains. No Vindhyan sediments seem to have

transgressed this range, but on its NW side there are again sandstone formations reminiscent of the Vindhyans, underlain by conspicuous rhyolitic volcanics and granitic rocks called the Malani Volcanics and Intrusions.

Malani volcanics and granites

Malani deposits follow unconformably over the Delhis and are themselves transgressed by sandstone formations of Vindhyan aspect. The *rhyolites* forming the bulk of this group are mostly reddish brown, with pink orthoclase, sometimes with sanidine-like feldspars, some oligoclase and frequent idiomorphic though mostly corroded quartz, idiomorphic hornblende phenocrysts or microliths, and some magnetite. The groundmass is mostly cryptocrystalline to microgranitic. Locally some more basic lavas, tuff horizons, and lenticular volcanic breccias are intercalated. Welded tuff beds (ignimbrites) seem only subordinate and are certainly not responsible for the relatively wide distribution of the acid volcanics.

The rhyolites are intruded by the slightly younger *Malani Granite*, a pinkish medium to coarse-grained granite, although less coarse than the Erinpura granite into which it is in some places intrusive. The main constituents of the granite are orthoclase and quartz with a varying amount of acid plagioclase; hornblende and biotite are present, but either may be dominant or altogether missing. A less frequent mineral is muscovite. Accessories are tourmaline and fluorite. The border zones of the granite are often porphyric and granite porphyries and quartz porphyries do occur. Rhyolitic intrusions can also occur within the granites. The extension of the Malanis must be considerable and although they are mostly covered by younger rocks of the Thar desert, Malani-like rocks outcrop in the NW Punjab. Also the Talchir boulder-beds of the Salt Range have Malani pebbles and boulders as an important constituent. East of the Aravallis there is no sure representative of the Malanis, which would here fall within the Lower Vindhyans. Some authors see a correlation in the porcellanitic tuffs of the Lower Vindhyans, but this comparison is not very convincing.

Sediments of the Trans-Aravalli Vindhyans

Between the western and eastern outcrops of the Vindhyans the narrowest gap is about 150 km. To the west and northwest of the Aravalli Range only the Upper Vindhyans are represented by normal sediments, and the Malani group can be no more accurately dated than as falling somewhere between the Delhis and the Upper Vindhyans. The sediments occur in widely scattered tabular outcrops and when the contact with the underlying Malanis is exposed it is mostly conformable, although the weathered surface of the volcanics and granites clearly indicates a hiatus.

Reddish brown sandstones and conglomerates form the lower part of the succession and grade upwards into limestones. The conglomerates, often more widespread than the sandstones, rarely occur at the base of the clastic rocks and are mostly fine-grained with pebbles of quartz and quartzites. Ripple marks and cross-bedding are frequent. The upper limestones are cherty and slightly bituminous. Although these sandstones and limestones have been correlated with the Kaimur and Bhander divisions of the eastern basin, this correlation is vague over such a great distance, and more so if one accepts two separate basins of deposition. Studies of cross-bedding by Auden, however, indicate that a current coming from the east has to be considered for the eastern as well as the western basin (Pascoe, 1959; see footnote p. 549). This fact is somewhat difficult to explain if the existance of a high dividing Aravalli Range is admitted for the time of deposition.

Similar to the rocks of the eastern basin, but here more widespread, these Trans-Aravalli Vindhyans often contain well-preserved trilobite trails and burrows elsewhere characteristic of the lowest Palaeozoic (Salt Range). The upper age-limit of the western Vindhyans is given by the overlap at Bap (NE of Jodhpur) of the Upper Carboniferous Talchir boulder bed with its content of boulders of Malani volcanics and Vindhyan limestones. As a lower age-limit we have the marked transgression over the Delhi group, often seen as a 90° unconformity where the Malani rocks are missing.

VINDHYANS AND THE ARAVALLI RANGE

On a regional scale the western as well as the eastern Vindhyans have been little disturbed by the Aravalli orogeny. From all the evidence, except Auden's most interesting remarks on the constant easterly current (see above), the Aravalli Range must have formed an effective barrier. This is particularly well seen where the Aravallis border the eastern Vindhyan basin. Here the boundary between the little-disturbed Vindhyan sandstones and the tightly folded rocks of the Aravalli Range lies along the *Great Boundary Fault of Rajputana* (actually a fault zone) running from SW to NE over 400 km. The fault movement must have been partly syngenetic with, and partly later than, the deposition of the Vindhyan rocks producing vertical displacements with the downthrow of the Vindhyans towards the southeast amounting to nearly 2000 m. How much movement of the strike-slip type was involved is difficult to ascertain. Approaching the fault zone, th

Vindhyan sediments become folded, the folds getting tighter towards the fault in the NW. Northeastwards the fault zone runs into the Ganges Plain and can be traced by subsurface features towards the Himalayan range. The surface features of the disturbance are steep and partly reversed, implying that a southeastwards thrusting of the Aravallis may have played a more important role than so far visualized (see Pl. I and Fig. 3). The intricate structures clearly show a relative movement from the NW towards the SE, remarkable when we consider that this is against the convexity of the whole range, which hinges around the marked *syntaxis at Chitorgarh* from a NNW-SSE strike in the southern part to a dominant NNE-SSW direction in the northern part. The latter, as we have already seen, is a strike direction which is widespread as a structural grain of northern Peninsular India.

In post-Delhi and early Vindhyan times the Aravalli must have formed an impressive mountain range which some authors believe to have been the size of the present Himalayas. The writer feels however that a mountain range of such a magnitude should have influenced its foreland (eastern Vindhyan basin) to a much greater extent than is so far known. Also the little that remains visible of the internal structures of the Aravallis (Fig. 3) does not show the tectonic features characteristic of a mountain range of Alpine type, with its typical deformation and where sheet thrusting is common. The importance of this major feature of Peninsular India on the history of the Himalayas will be reviewed in a concluding chapter.

ISOLATED NORTHERN-MOST (NE AND NW) OUTCROPS OF THE PENINSULAR SHIELD ELEMENTS

Here we are mainly concerned with the northernmost (NE and NW) outcrops of still true shield elements, which as isolated occurrences are not visibly connected with the main shield mass. They limit the Himalayan foreland and seem directly responsible for some of the most striking Himalayan features—the syntaxis at its western

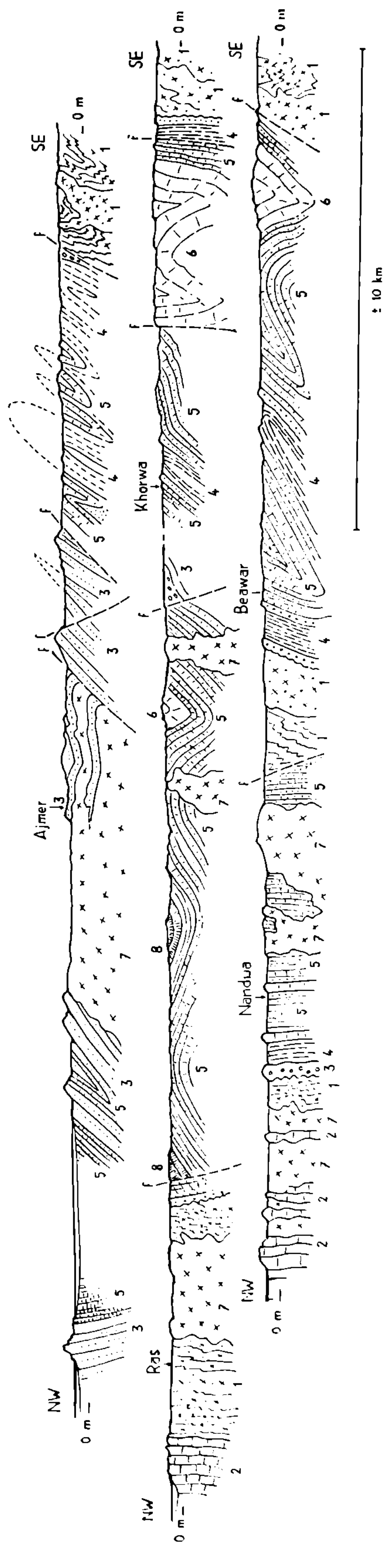


Fig. 3 *Geological sections through the northern Aravalli ranges;* mostly after A. M. Heron (1953)

1 banded gneisses and migmatites (Pre Aravallis)
2 Raialo limestones
3 Alwar conglomerates and quartzites (Lower Delhis)
4 biotite schists and amphibolites, Ajabgarh (Upper Delhis)
5 calc schists and quartzites
6 marbles, Ajabgarh
7 Erinpura granite
8 amphibolites in Ajabgarh

and eastern ends, as well as the configuration of the foreland basin.

Northeastern shield elements (Assam)

The northeastern part of the main shield ends in the Rajmahal Hills (Bihar), where the Ganges River turns southwards through the large Ganges-Brahmaputra depression. At Rajmahal the Archaean gneisses are covered by gently eastward-dipping Gondwanas, with a poorly developed Talchir boulder bed, thick but shaly coal beds, and a large cover of traps of Jurassic age. The gentle eastward dips are significant in marking the western border of the *Ganges-Brahmaputra depression.* A basement fault running N-S under the Ganges alluvium as the northern continuation of the eastern boundary of the Rajmahal Hills (shown on the airborne magnetometer maps, MATHUR and KOHLI, 1963), may suggest a graben-like structure for this vast feature.

The eastern border of the depression is formed by the large but isolated *Shillong plateau,* which is followed in the east by the smaller *Mikir Hills.* Both Shillong and Mikir Hills are detached remnants of the Indian shield and project far towards the eastern Himalayan syntaxis. On their southeastern side they are bordered by the southwestwards and southwards striking Tertiary ranges of southern Assam and western Burma. Northwards they are drowned under the Brahmaputra alluvium, with some remarkable *inselbergs* standing out as sharp hillocks even to the north of the Brahmaputra River (Tezpur and Dubri Hills). These northernmost shield elements narrow the stretch of the alluvial and Tertiary-filled Himalayan foreland to no more than 35 km.

The Shillong Plateau reaches over 1500 m above the alluvial plain of the Brahmaputra Valley; its southern slopes are abrupt scarps following fault zones rejuvenated in late Tertiary and probably still somewhat active considering the frequent earthquakes in the Shillong region. Northwards the plateau slopes towards the Brahmaputra River with a cover of alluvium and is still partly visible north of the river in the sharply outlined inselbergs.

The Archaean Shillong rocks can be subdivided into the *Shillong group* and the *older gneisses and granites.* The Shillong group outcrops along the southern and eastern side of the uplift and consists of an unknown thickness of mica, chlorite and hornblende schists, as well as amphibolites representing partly altered basic rocks. With a steep but conformable contact they adjoin micaceous quartzites with intercalated conglomeratic layers, reported to be of somewhat younger age (General Reports Geol. Survey, 1937-38). Some haematite quartzites reminscent of the Iron Ore formation of southern India are mentioned (GOSH, 1938). Locally sillimanite-cordierite quartz rocks occur within the Shillong schists in which the enriched sillimanite together with corundum can be of commercial importance. The green schist facies of most of the Shillong rocks contrasts with these high-grade metamorphics reported to be influenced by granite contacts.

The largest portion of the Shillong area is formed by Archaean gneisses and granites. The gneisses are finely banded, grey to pinkish in colour and contain microcline, biotite, subordinate quartz and plagioclase; the intrusive granites are mostly porphyritic with large flesh-coloured microclines, some acid plagioclase, orthoclase, and biotite. These granites also intrude the Shillong schists, but are less frequent in the Shillong quartzites.

The structural pattern of the Shillong uplift is oriented predominantly E-W. The schists generally have steep dips, often south-dipping in the north and north-dipping in the southern area, and indicate some kind of fan structure. The granites contain E-W joints, some intruded by dolerite dykes comparable to trap-like rocks on the southwestern part of the Shillong uplift, which again have similarities with the already mentioned Gondwana traps of Rajmahal, of Jurassic age.

To the NE of the Shillong plateau the *Mikir Hills* form the last outcrops of shield rocks towards the eastern Himalayan syntaxis. Like the Shillong they are fringed by Tertiary rocks with faulted contacts and alluvial deposits to the north. Gneiss and granites dominate, but apart from some porphyritic granites, differ from the Shillong rocks by a scarcity of alkali feldspars. Plagioclase, biotite, and hornblende are frequent. Quite surprising are some outcrops of coarse charnockite gneisses (hypersthene gneiss), identical with the SE Indian (Madras) types and representing the only charnockite rocks so far found in the northern part of the Indian shield. The steep dips in the gneisses as well as the foliation in the granites strike E-W, though local changes are frequent.

North of the Brahmaputra River we find some granitic and gneiss hills as remnants of the northwards-drowned Shillong plateau, only 35-40 km from the Himalayan foothills. The writer visited some of these hills in 1963 while travelling from eastern Bhutan to Dubri. These inselbergs form surprisingly steep, thickly forested hills contrasting sharply with the flat, rice field areas surrounding them. Several hills are over 500 m higher than the level floodplains. The whole morphological aspect suggests a recently drowned landscape.

A migmatitic, often granitic, biotite gneiss is frequently met. The light-grey gneisses expose an irregular banding which, becoming progressively diffuse, grades into locally massive medium-grained layers of biotite granites. Gneisses and

granites are rich in alkali feldspars with dominant microclines and acid plagioclases. Olive-brown biotites are frequent; muscovites are subordinate. The former can be locally enriched in bands and irregular patches. The rocks are mostly fresh and cataclastic features are absent. In the southwestern hills pinkish granites dominate, contrasting sharply with the migmatic biotite-granite gneisses. The massive rocks show a surprisingly high amount of stress and cataclastic alteration. Microclines and perthitic orthoclases, together with acid plagioclases are frequent. They occur in larger grains often surrounded by a mass of approximately equally sized cataclastices. The quartzes show very strong stress shadows. While the feldspars are surprisingly fresh, the subordinate biotite is fully chloritized. Interesting accessories, apart from some epidotes, are garnets. The contact of these cataclastic pink granites and the above mentioned migmatites was not seen, since each forms a single, isolated hill. The pink granites and the biotite gneisses correspond to the Archaean-type crystalline of the Shillong uplift, where microclines are an important and, for these Archaean rocks, a most characteristic constituent.

The northeastward continuation of the Shillong-Mikir massif can be followed from recent drilling and geophysical information below a thick cover of Tertiary and Quaternary sediments. In Sibsagar, 100 km NE of the last Mikir Hills outcrop, the highly faulted basement is covered by 3800 m of Tertiary and Quaternary, with the Middle to Upper Eocene, approximately 300 m thick, transgressing directly onto the crystalline basement (Mathur and Kohli, 1963).

The structural pattern of most of the Assam oil fields shows faulting in preference to folding; some of the fault zones are rejuvenated basement features and have controlled to some extent the sedimentation of the Tertiary deposits. A very marked unconformity separates the younger Miocene sediments, formed in predominantly continental environments, from the older Tertiaries. These younger sediments may correspond to part of the Siwalik system of the nearby Himalayan foothills in the north. The thrust zone forming the contact against the mobile belts of the SE Assam and Burma ranges, with a thrust direction towards the Assam basin, begins south of the Mikir Hills and seems to join the eastern syntaxis with the main Himalayan boundary thrust.

Northwestern shield elements (Punjab)

Similar to the NE shield elements extending towards the eastern Himalayan syntaxis, in the NW we can observe isolated shield rocks which trend towards the western Himalayan syntaxis, although outcrops are of a much smaller scale than in the Assam region. We have already noted that the Aravalli ranges can be traced running nearly at right angles towards, and most probably *below*, the Himalayan range. The northwestern shield elements belong to the Trans-Aravalli rock sequence, at least as far as the Purana rocks are concerned. Two main regions will be summarily discussed: the *Hissar region*, 120 km WNW of Delhi which can be regarded as the most northwesterly Aravalli outcrop, and the *Kirana Hills* in the northern Punjab, between 80 and 150 km WNW of Lahore.

In the *Hissar region* the Tusham, Khanak, and Nagana Hills show outcrops of steeply dipping, fine-grained rhyolitic quartz porphyries which follow conformably above the tightly folded chiastolite schists (Tusham). The metamorphism of the argillaceous sediments and the steep dip of the younger porphyries clearly show that these outcrops are still related to the northwestern Aravallis, of which they actually form the normal continuation. The schists are regarded as Delhis or Aravallis, while the porphyries could represent the volcanic Malanis of the Trans-Aravalli Vindhyan formations.

The Kirana Hills, form outcrops of the most northwesterly shield elements and are, as is the Shillong-Mikir massif in the NE, of special interest since they reach far towards the western Himalayan syntaxis; their westernmost hill is only 70 km south of the Salt Range. They clearly indicate that the large desert tract of the northern Punjab is still underlain by shield elements.

The Kirana Hills extend in four separate groups (Kirana, Chiniot, Sangla and Shahkot) for about 100 km from E to W. Their steeply rising topography and the intense black desert coating of their serrated ridges are impressive features. The predominant rocks are hardened grey-greenish shales and slates containing small biotites, and coarse- to fine-grained reddish quartzites. Of these the argillaceous beds are more concentrated in the eastern hills and the quartzites in the western hills. Both, the slates and the quartzites, are accompanied by small bands of diabase together with thin layers of rhyolites and rhyolitic tuffs. The bedding in both groups is generally steeply dipping, often with a northerly component; the strike varies, but two main directions are dominant—in the western hills a NW-SE strike, in the eastern hills a NE-SW direction. This rather abrupt change in strike of 90° is quite surprising, for the eastern hills conform still to the regional Aravalli strike direction while the western ones show a trend parallel to the Himalayan range and seem to strike towards the bend in the Salt Range, where an equal change from NE towards the NW is visible.

The sediments of the Kirana Hills have been compared with those of the Ajabgarh division of the Delhi system, or with the Lower Vindhyan

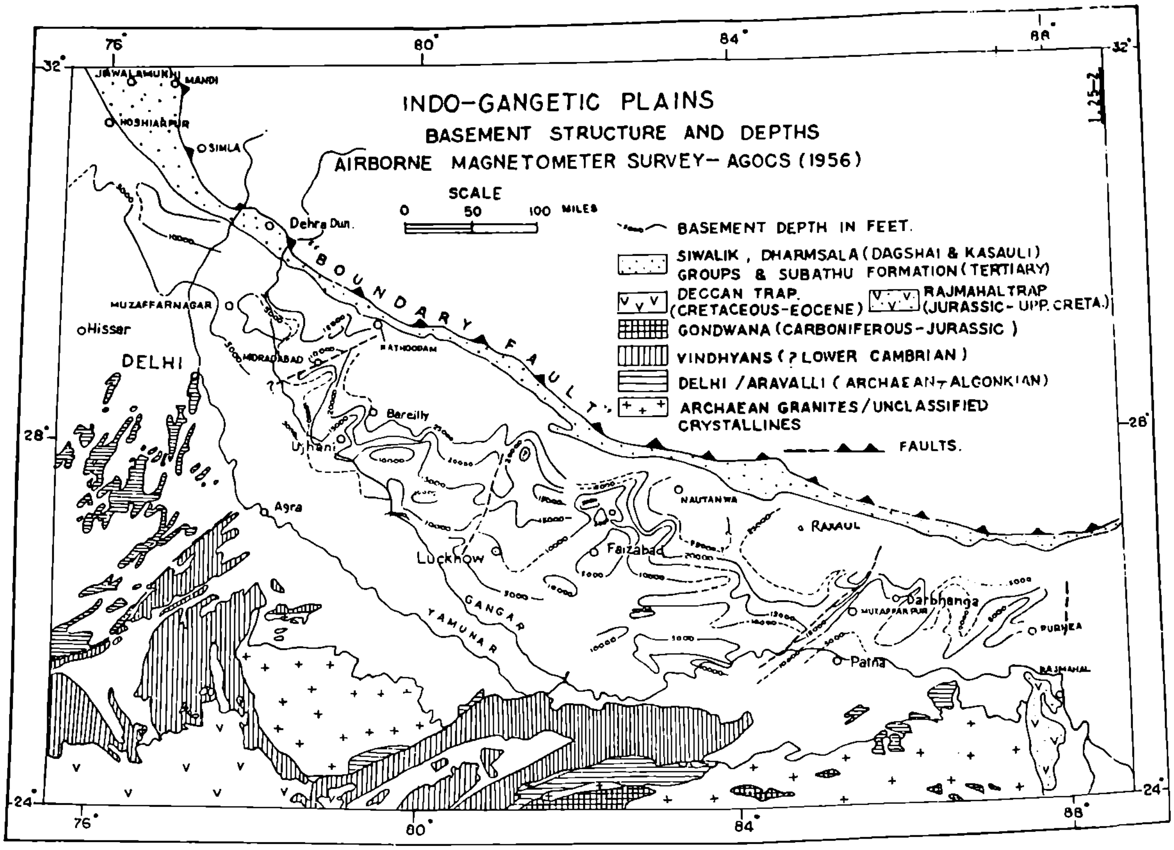


Fig. 4 *The basement structures and depth of the Indo-Gangetic plain;* reproduced directly from MATHUR and KOHLI (1963)

formations, for which one must assume a marked decrease in Malani volcanics and an increase in sediments (PASCOE, 1959). The small layers of rhyolites could indeed represent highly reduced Malani volcanics, but the disconnected outcrops and the high secondary alteration of the rocks here makes all correlation somewhat doubtful.

RELATIONS WITH THE HIMALAYAN FORELAND

In the foregoing we have summarized the most important surface features of the northern part of the Indian Shield as far as they could be of importance in understanding the framework of the Himalayas and their influence in particular on the Himalayan foreland, and the Brahmaputra, Ganges, and Indus alluvial plains. The direct relations of the shield elements with the Himalayas are masked today by the extensive Quaternary foreland cover; in this the most important geological facts to be ascertained are the depth and configuration of the basement, as well as the amount of younger sediments. An intensification of the oil search in these foreland basins has yielded most interesting results in this respect, but unfortunately very little has yet been published. Some results of a regional airborne magnetometer survey covering the Ganges Plain have been published (MATHUR and KOHLI, 1963) though the interpretation is still open to doubts (Fig. 4). These results have been incorporated in our tectonic map (Pl. I B). Here we are more concerned with the problem of whether or not a continuation of the shield elements towards, and even *under* the Himalayas, is indicated. This question seems to be positively confirmed by the magnetometer results. The surprisingly irregular pattern of the basement under the Ganges Plain conforms to the surface features of the shield. It further shows that the basement depths are rather shallow in many areas until near the Himalayan foothills, and that little room exists for the large development of sediments which one would expect in the foreland of a mountain chain of Himalayan dimensions. How much of this foreland is actually covered by the southward-thrust Himalayas is again a matter for discussion in a concluding chapter.

THE HIMALAYAS INCLUDING THE SALT RANGE AND THE KARAKORUM

CHAPTER III

SALT RANGE

In an intermediate position between the Indian Shield and the Himalayas, the Salt Range, with its excellent exposures and fossiliferous horizons, has attracted attention since the earliest times of geological investigation. After the first comprehensive report by WYNNE in 1878 the Salt Range has become of particular interest. It is one of the rare regions in the world where marine Permian is normally followed by marine Trias, and the important boundary between Palaeozoic and Mesozoic can be studied at excellently exposed sections. These have as their basal member the Saline Series, which has for many years provided one of the main controversies in Indian geology and whose reputed age has varied between Precambrian and Tertiary. Physiographically, stratigraphically as well as structurally the Salt Range differs considerably from the westernmost Himalayas only 80 km distant, to which its history is linked by the various orogenic phases, the last one reaching far into recent times.

The range, over 200 km long, strikes predominantly E-W, with a remarkable northwards-directed bend at the Indus River crossing which seems a forerunner of the garland-like folds of the Baluchistan ranges. The Salt Range does not reach far west of the Indus River crossing but can be followed eastwards as far as the bend of the Jhelum River to which the eastern range runs parallel. Its eastern end seems to coincide with the western Himalayan syntaxis, which in these more southern areas is, as far as can be seen from the Tertiary outcrops, much less accentuated.

For excellent accounts of the Salt Range and in particular its saline basal deposits we owe much to GEE (1934, 1945, 1950) who has mapped the whole region in great detail. He has contributed substantially to the highly disputed age problem of the saline deposits. Recently SCHINDEWOLF and SEILACHER have given a most interesting account related to the two main problems of the Salt Range — the Palaeozoic-Mesozoic boundary (1954) and the age of the saline deposits (1955).

Several unconformities are responsible for a very uneven distribution of the sediments in the Salt Range; the most important are the Upper Carboniferous Talchir unconformity, the basal Eocene unconformity, and the Miocene Siwalik unconformity. Post-Cambrian deposits are preserved mostly in the western part of the Salt Range while the Cambrian section is well exposed in the eastern extension of the range (Figs. 5, 6 and 7).

The so-called *Saline Series* form the oldest rocks outcropping in the Salt Range. Its base is not known, and over 500 m are exposed in the narrow gorges cutting the southern scarp of the range. The saline formations consist of gypsum at the very base, covered by alternate salt marls and banded rock-salt. Of special interest are the contacts with the thick overlying *Purple Sandstone;* disharmonic folding between the incompetent salt masses and the competent sandstones has caused local anomalous contacts, which have played an important role in the age discussion of the saline deposits. It would be along these contacts that the main thrusting of Cambrian over Tertiary would be placed by the advocates of a Tertiary age of the salt. Less disturbed sections show however that normal stratigraphical relations do exist, and this has been carefully investigated by SCHINDEWOLF and SEILACHER (1955). In the topmost gypsum bed, just underlying the Purple Sandstones, there are thin bands of dolomite followed by an alternation of anhydrite and dolomite. Included within this uppermost gypsum is about one metre of a volcanic trap-like layer, with a chilled, fine-grained and vesicular border zone. Of special interest are thin black bituminous papery shales which occur within the fine-bedded anhydrites and dolomites (dysodil after SCHINDEWOLF). The writer has seen similar bituminous papery shales frequently marking the upper limit of thick saline deposits in the Middle East, in normal sedimentary relations or as inclusions in salt domes. Paper shales are typical for the evaporitic cap rocks in many of the famous Persian oil fields. They are extremely widespread and not related to any particular stratigraphic

horizon, a fact quite important in the age dispute of the Saline Series.

Following and conformably covering the top gypsum one finds the *Purple Sandstones*, beginning with the thin-bedded shaley sandstones and red-brown shales, succeeded by thick-bedded purple fine-grained quartz sandstones. Cross-bedding is frequent and on the bedding planes one can note ripple marks, mud cracks and salt pseudomorphs. Some fossil tracks are the only organic remains in this section. Above the 150 m thick sandstones, which form conspicuous scarps, follow the *Neobolus Shales*, separated from the sandstones by a very thin quartz conglomerate which grades from the sandstones and shows no trace of an unconformable contact. The overlying shale zone is quite complex, with thin dolomitic bands, oolites and grey pyritic clay shales with a surprisingly low lithification. The grey to greenish colour of the *Neobolus* section contrasts strongly with the Purple Sandstones. The main interest here is the Lower Cambrian trilobite fauna *(Redlichia)* and the well-preserved trails and burrows, masterfully reproduced by Seilacher (SCHINDEWOLF and SEILACHER, 1955).

Above the shale section follow the *Magnesian "Sandstones"*, actually a genuine dolomite which may have been formed from a dolo-arenite. The 80 m thick dolomite contains in its middle part a shale section not unlike the *Neobolus* Shales. Similar fossils, trails, and burrows as in the *Neobolus* horizon have been found. Following the marine *Neobolus* Shales, the dolomite may actually represent a shallow-water deposit leading to the overlying *Salt Pseudomorph beds* which indicate a recurrence of the evaporitic conditions. They consist of red to violet thin-bedded slatey sandstones and shales rich in salt pseudomorphs. Thin dolomitic bands are still present in the lower part. Fossils are completely missing.

On the basis of the *Redlichia* fauna, SCHINDEWOLF assigns to the whole section a *Lower Cambrian age*. The transitional contacts from Purple Sandstones into the fossiliferous shale beds and again the transition from the dolomites into the Salt Pseudomorph Beds seem to confirm this view. The visible Cambrian outcrops thus represent a complete cycle from continental to marine and again to continental conditions. The deepest saline horizons fit well into this picture, and the contact with the Purple Sandstone, carefully investigated by SCHINDEWOLF, leaves little doubt that a true normal section is here represented and that the salt horizons are of Lower Cambrian or even earlier age. This should end a most intense and old controversy regarding the age of the

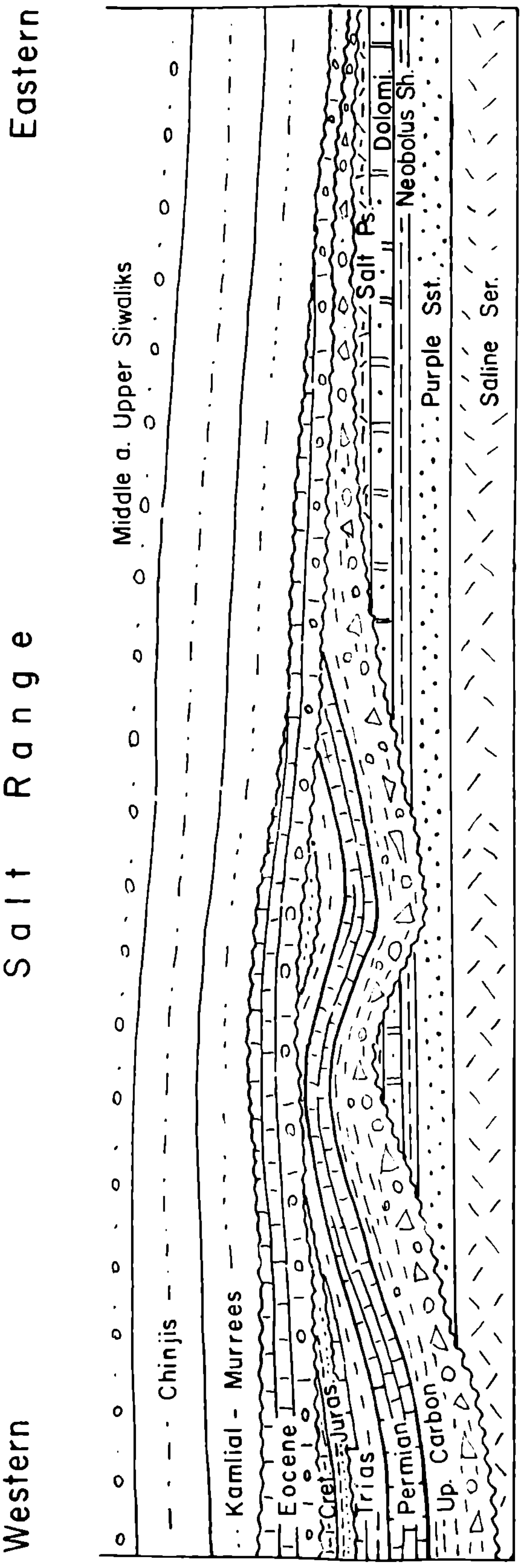


Fig. 5 *Distribution of Salt Range sediments* (not to scale); redrawn after E. R. GEE (1945)

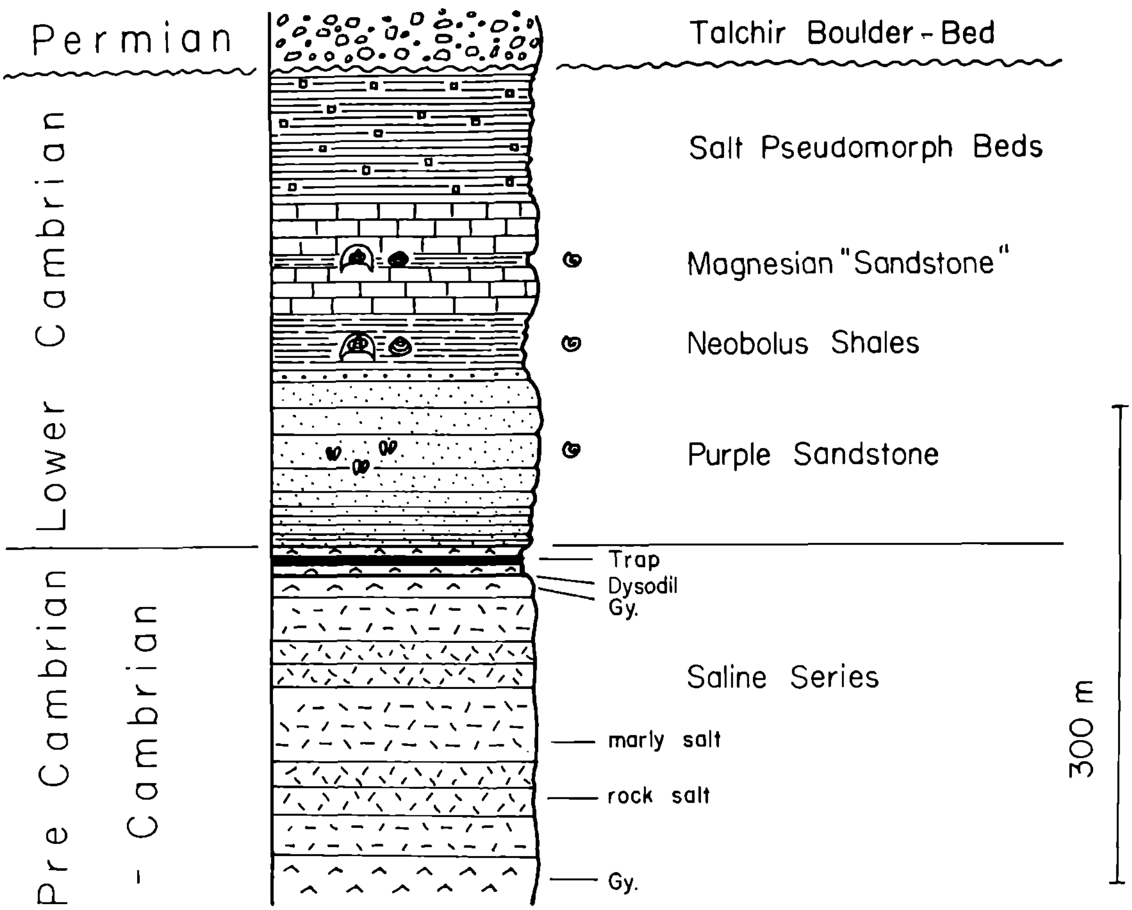


Fig. 6 *Stratigraphy of the Cambrian, eastern Salt Range;* redrawn after SCHINDEWOLF and SAILACHER (1955)

Saline Series, in spite of the still surprising contaminations by microscopic Tertiary to Recent plant and insect remains. Since the latter have been found also in definitely proven Cambrian and even older rocks, the suspicion of contamination is fully justified. Cambrian or older salt formations have long been known from salt domes of the Persian Gulf, but only recently have the careful investigations of HUCKRIEDE, KÜRSTEN, and VENZLAFF (1962) as well as STOECKLIN (1961) from southeast Iran produced excellent Cambrian sections with a *Redlichia* fauna above red sandstones, reminiscent of the saline Hormuz formation of the Persian Gulf. The comparison of the Hormuz formation with the Saline Series of the Salt Range has often been an important argument in favour of the Lower Palaeozoic age of the latter (LEHNER, 1945, 1947). As far as the Salt Range is concerned the arguments for or against an old age of the Saline Series, swinging like a pendulum from the Tertiary to the Cambrian and back, are very well summarized by SCHINDEWOLF and will here not be discussed further.

With a sharp, unconformable contact, the Lower Cambrian of the Salt Range is transgressed by the famous *Talchir boulder beds*, one of the most constant horizons of the Salt Range scarp (Fig. 6). With a thickness varying from a few metres to over 100 m, the rock has a sandy to argillaceous matrix in which are embedded irregular boulders and pebbles of Cambrian rocks in the lower horizons and of more crystalline origin (granites and rhyolites of the Malani type) in the upper layers. Generally accepted as glacial tillite, the Talchirs contain Lower Gondwana leaf impressions and spores which suggest an *Upper Carboniferous age*, further confirmed by some marine fossiliferous incursions in its upper horizons. The marine influence increases in the higher levels and finally the Talchirs are followed by a widespread marine invasion, which after a more detrital sedimentation giving such formations as the Speckled Sandstones and Lavender Clays, culminate in the well-known *Permian Productus limestones*. The latter are missing in the eastern Salt Range, eroded prior to the Eocene

transgression. In the western Salt Range they grade without a break into the Lower Triassic. It is here that SCHINDEWOLF has described the famous Chidru section (1954).

We can distinguish Lower, Middle and Upper *Productus* Limestones, the Lower and Middle developed as siliceous, mostly thick-bedded to massive coralliferous limestones while the Upper consists of an alternation of thin-bedded calcareous sandstones, marls and limestones. It contains a good marine Upper Permian fauna, particularly rich in the highest horizons. Here SCHINDEWOLF describes a most carefully sampled section stradling the Palaeozoic-Mesozoic boundary. Above a sandy, somewhat dolomitic, limestone with a well-developed Upper Permian brachiopod fauna follow 3-4 m of a calcareous, softish sandstone apparently without fossils, overlain by sandy limestones with greenish clay nodules already displaying a Lower Triassic *Ophiceras* fauna. In spite of a well-exposed transition with no change in lithology between the Permian and the Triassic horizons, a clear-cut and very sharp faunal break is evident. From a brachiopod fauna with some cephalopods *(Cyclolobus)* of Upper Permian age we suddenly enter beds with a pure cephalopod fauna of Lower Triassic affinities. It could be questioned, however, and SCHINDEWOLF seems well aware of this possibility, whether the lowermost Trias is not missing, since the lowest horizon with *Otoceras*, found in the Kashmir Trias is not developed in the Salt Range. This fact would hardly change the surprisingly sharp faunal break at this important boundary. It is not the place here to enter into speculations on this subject and the reader may follow the respective discussions in SCHINDEWOLF's careful study (1954).

The Lower Trias follows with the same lithology as seen in the Upper Permian but grades towards the upper part into massive dolomites, with some intervening sandstones indicating depositional changes for the middle part of the Trias. The dolomites are placed into the Upper Trias mainly on lithological grounds. An emergence followed the dolomite deposition, exposing and partly eroding the dolomites to produce a brecciated surface with a bauxitic matrix. The dolomites are unconformably overlain by variegated shales with *Jurassic plant remains*, followed by more marine *Upper Jurassic limestone* deposits. It seems most likely that Jurassic deposits did not cover the whole area of the Salt Range and were originally missing in the east. The boundary against the *Cretaceous* appears conformable; glauconite-bearing Belemnite shales seem to pass into the Cretaceous, which in the western range is followed by marine, though shallow-water, sandstones with some carbonaceous matter. Most likely Cretaceous rocks were not deposited over the eastern Salt Range, and the border of the Cretaceous sea transgressed the range obliquely. A strong uplift and subsequent erosion followed in the late Mesozoic, and the eroded landscape was invaded by the *Eocene* (Paleocene) *Ranikot Sea* from the south and west, depositing the fossiliferous Ranikot limestones. In the eastern Salt Range the Eocene transgresses directly into the Talchir boulder beds. Above follow the *Laki* foraminiferal shales and limestones of Lower Eocene age, the deposition of which was arrested by renewed though local uplifts. In the *Middle Eocene Khirthar Series* lagoonal conditions resulted in evaporitic deposits (the Kohat saline series) which played such an important role in the age battle of the Salt Range Saline Series.

Locally, freshwater clays and some shallow marine deposits persist into the *Middle Eocene*, but after these were laid down a strong uplift affected the whole area and resulted in a strong denudation of the Salt Range. Upper Eocene and Oligocene deposits are missing, and only with the *Miocene* did the brackish to freshwater, or fluviatile, *Murrees* begin to be deposited north of the Salt Range in the Potwar basin. The Murrees were followed by the *Siwaliks*, progressively transgressing over the Salt Range south of the Potwar region. Murrees and Siwaliks will be discussed in connection with the Punjab Himalayas in the next chapter.

The strong orogenies beginning in the Upper Siwalik and lasting into Recent times were mainly responsible for the present structure of the Salt Range. As already mentioned, the Salt Range is a relatively simple structure contrasting with the tectonics of the westernmost Himalayas north of the Potwar basin (Fig. 7). It is essentially a faulted and folded monocline, rising southwards with a marked scarp to the south and dipping gently into the Potwar Tertiary basin. The western part of this monocline shows a pronounced northwards bend at the crossing of the Indus River, with a corresponding southwards-directed bulge to the west. N-S directed strike-slip fault movements are here involved. Similar bends increase and widen considerably towards the SW in garland-like folded ranges of Baluchistan (see tectonic map Pl.I B). Tectonically they may also be comparable to a less pronounced and considerably smaller Himalayan syntaxis.

The southern scarp of the Salt Range is formed by steep southwards-dipping faults which cut the monocline into a system of large blocks. Some of these faults are however reversed, even turning locally into thrust faults (Fig. 7). The action of the underlying saline masses has certainly enhanced disharmonic tectonics and may be responsible for many local complications and may actually indicate *a more severe thrusting in depth.* It could be such a thrusting that prevents a more diapiric rise of the underlying salt zone. The

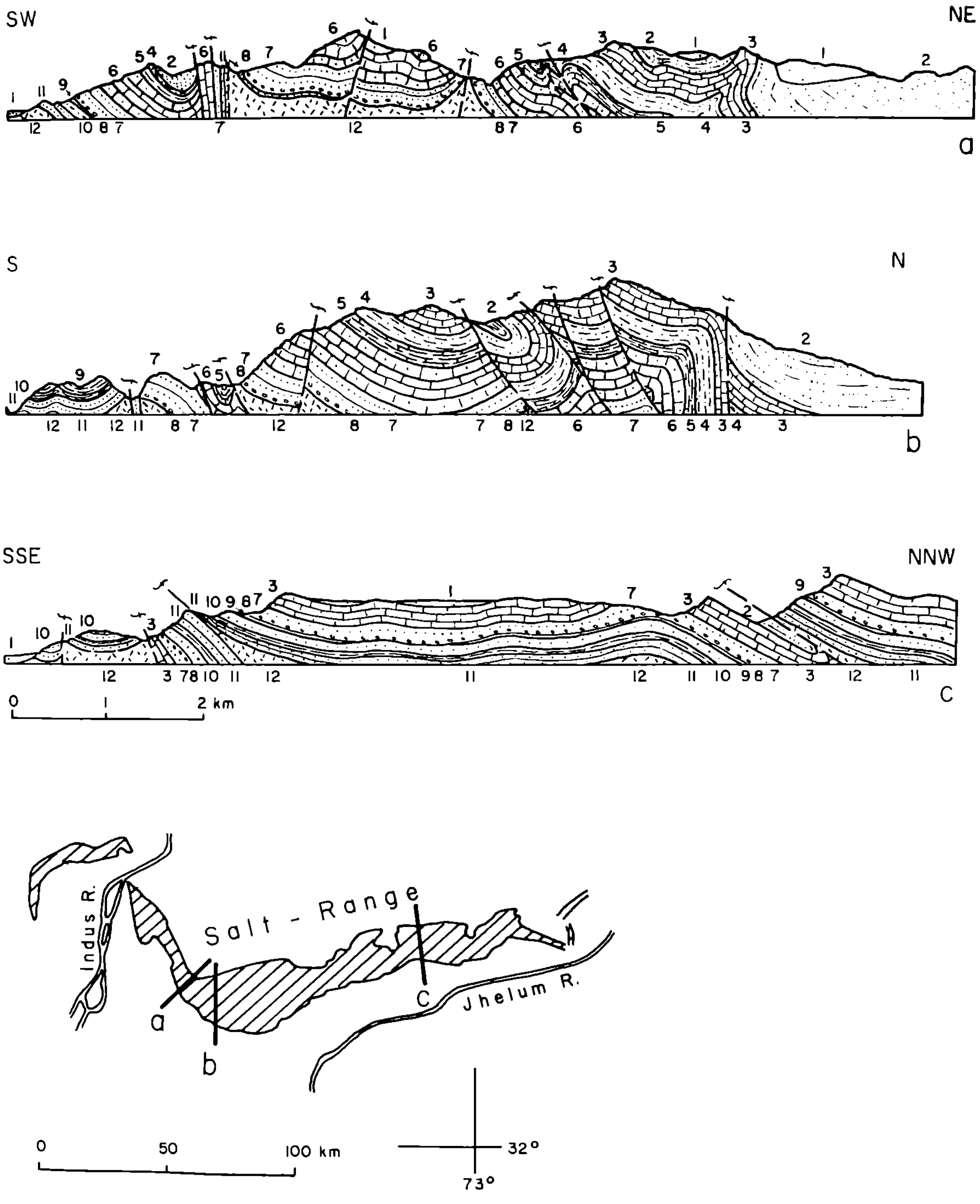


Fig. 7a, b, c *Sections through the Salt range;* redrawn after E. R. Gee (1945)

1	Pleistocene alluvium
2	Siwalik
3	nummulitic (Laki and Ranikot)
4	Jurassic
5	Trias
6	*Productus* limestone
7	Speckled sandstones
8	Talchir boulder bed
9	Salt Pseudomorph beds
10	Magnesian sandstones
	Neobolus shales
11	Purple sandstones
12	Saline Series
ſ	fault, usually reversed

influence of salt masses on disharmonic tectonics is well known. It would be a stimulating task to find out how much the detachment of the thrust of the Himalayas from the underlying Shield rocks is actually favoured by plastic saline deposits. Unfortunately nothing is known of the distribution of saline rocks of the Salt Range type in the foreland and below the Himalayas. It seems, however, most likely that Vindhyans of the northern Indian Peninsula, which do to some extent resemble the Purple Sandstones of the Salt Range, change northwards into marine deposits, passing through an evaporitic facies. This evaporitic belt could be the very horizon which favoured the detachment of the Lower Himalayas from the northwards extension of the Indian Shield. Evidence from the Cambrian outcrops within the mountains is negative, but those Cambrian rocks may belong to a more northern facies area.

CHAPTER IV

KARAKORUM

As the Salt Range south of the Himalayas bridges the gap from the Peninsular Indian shield to the Himalayas, so the Karakorum mountains are an important link between the Himalayas in the south and the Central Asiatic mountain nucleus, the Pamirs, in the north. This latter mountain group actually forms the largest positive surface mass in the world. The link is however more a structural one, since the Karakorum has its own quite independent stratigraphical development in spite of some marginal adjustments to the northern and southern elements.

For this highly glaciated range—28-50% as compared to 8-12% for the Himalayas and 2.2% for the Alps (SCHNEIDER, 1961)—with its light-coloured granitic and gneissic rocks the name *Karakorum* (black gravel or stones), derived from the Karakorum Pass which does not even cross the range, is certainly misleading, and the older term *Mustagh* (Snow Mountain) would seem more appropriate.

Scientific investigations attached to large mountain expeditions began over 100 years ago (GODWIN AUSTEN, 1861) in contrast to the more one-sided alpinistic work in the Himalayas. With the beginning of the 20th century we find the famous Italian expeditions (DUCA DEGLI ABRUZZI, 1909 and DUCA DI SPOLETO, 1929) whose main purpose was the geographical investigation of the Central Karakorum, but which also included pioneer geological work. From these expeditions resulted the monumental work of DAINELLI (1934) and DESIO (1936), who together with NOVARESE were attached to the DUCA DI SPOLETO expedition. DESIO has continued the Italian tradition which culminated in the ascent of K2 (Mount Godwin Austen) in 1954 (DESIO, 1955; DESIO and ZANETTIN, 1956, 1957). Recently DESIO has extended his research more into the western Karakorum and the Hindu-Kush (DESIO, 1959) and we are looking forward to his forthcoming geology of the Karakorum which is in preparation. DE TERRA mapped the southeastern Karakorum in connection with his regional studies as a member of the TRINKLER Expeditions (1932, 1935). AUDEN, in his inspiring paper, *Traverses in the Himalayas* (1935), includes his studies of the Central Karakorum. Coming from the Tibetan side, NORIN (1946), has given an excellent account of the northern and eastern Karakorum (Aghil ranges). Recently SCHNEIDER, of the German Karakorum Expedition, investigated the western Karakorum, where his interest centered on a structural study in connection with the convergence of the Central Asiatic mountain ranges (SCHNEIDER, 1956, 1957, 1960, 1961). During the Austrian Karakorum Expedition of 1956 GATTINGER studied the wider Baltoro region and was able to complete much of what had been already found by DESIO's investigations. His results were published only in 1961, with SCHNEIDER's results included in his regional studies; this general account and accompanying compilation map gives the first overall picture of the Karakorum. Unfortunately the more recent publications by DESIO and coworkers have not been considered and are not even mentioned in the list of references. In a very recent note DESIO has strongly contested some of GATTINGER's work (DESIO, 1963).

The *Main Karakorum*, also called the *Mustagh Karakorum* (SCHNEIDER, 1957), extends in an ESE-WNW direction for over 350 km from the confluence of the Siachen and the Shyok Rivers in the southeast to the Ishkuman River (NW of Gilgit) in the northwest. The *SE Karakorum* can be traced into the Kailas Range of the Transhimalayas, while the NW Karakorum, by turning into an east-west direction, following the Himalayan syntaxis south of the Pamir plateau, continues into the *Hindu-Kush* and its southwards-diverging ranges. Just northeast of the *Mustagh Karakorum* appears the less well-defined *Aghil Range,* while to the southwest the main range is followed by the *Rakaposhi Range*, which plays a most important role in the Himalayan-Karakorum relations.

The clear subdivision of the main range into well-outlined chains following the general ESE-WNW strike is based on the parallelism of the main rock formations. In the eastern Karakorum

marine sediments from the Middle Palaeozoic to the Upper Mesozoic have been recognized because of their lower grade metamorphism. This metamorphism increases over the Middle Karakorum towards the western part of the range, where the higher grade metamorphism coincides with an axial culmination (SCHNEIDER, 1957).

The constant strike of the various lithological and structural elements of the Karakorum allows a subdivision of the main range into several distinct zones, each lithologically and structurally a more or less well-defined unit. A five-zone subdivision has been proposed by SCHNEIDER (1957) for the NW Karakorum, and this can, with some modifications, be applied to the whole range. SCHNEIDER's generalized section (Fig. 8) shows the NW Karakorum range as a two-sided orogene, with a steep northwards vergence in the northern zone and a marked south vergence in the southern zones, separated by an axial uplift coinciding with the central range. Steep thrusting is found on both sides of the axial uplift, but true overthrusts (nappes) are missing in the Karakorum.

Beginning in the south SCHNEIDER has numbered the various units from I to V, and calls them: I, the Rakaposhi Range; II, the Chalt schist zone; III, a zone of old schists and gneisses, grading into IV, the axial zone with its predominantly plutonic rocks, and the zone V, called the Tethys Karakorum. GATTINGER (1961) has subdivided the whole range into seven units, which include the various zones of SCHNEIDER. From north to south he mentions: 1, the Tethys Karakorum with its little-metamorphosed Palaeozoic and Mesozoic sediments (zone V of SCHNEIDER); 2, the Tethys thrust zone, a tectonic feature so far not recognized and consisting of remnants of stronger metamorphosed Tethys sediments thrust southwards over the axial and central crystalline zones; 3, an axial zone of young granitic intrusions of Alpine age (zone IV of SCHNEIDER); 4, a central crystalline zone south of the axial intrusion (zone III of SCHNEIDER); 5, a Schuppen zone corresponding to the Chalt schists of SCHNEIDER's zone II; and 6, a southern border of crystalline (including zone I of SCHNEIDER). A further element 7, is the so-called intru-

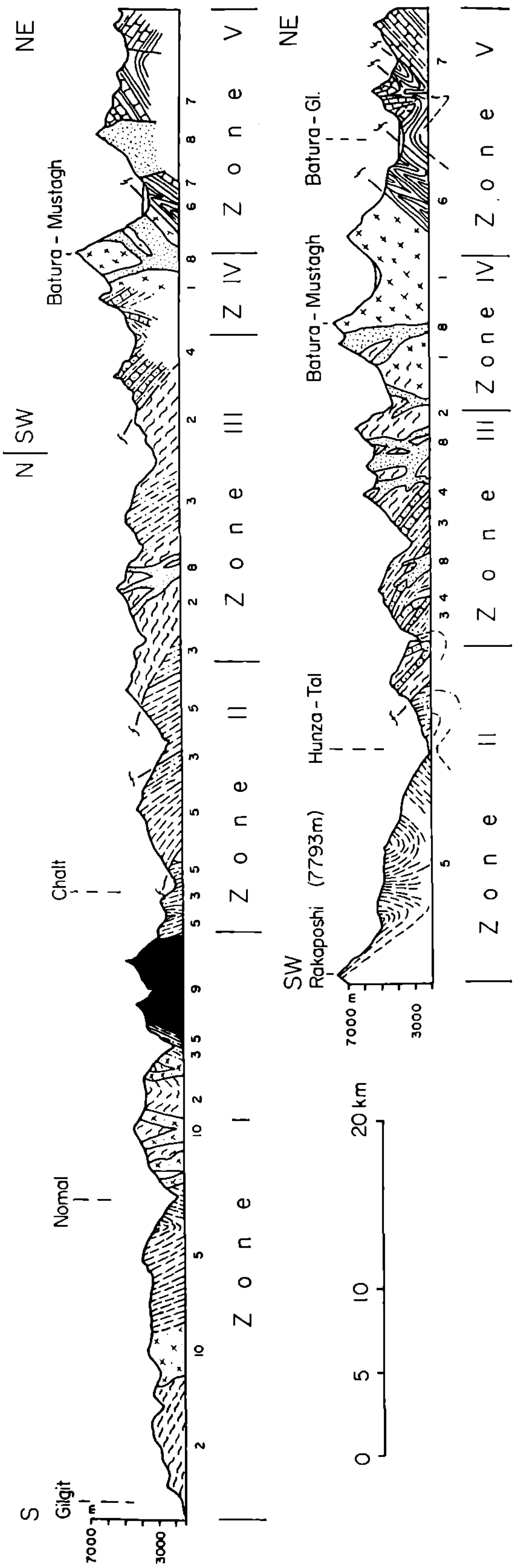


Fig. 8 *Geolocigal section through the NW Karakorum;* redrawn after H. J. SCHNEIDER (1957)

1 central granodiorite
2 schists and gneisses
3 garnet schists with amphibolites
4 zone with marble bands
5 phyllites and green schists
6 Pasu phyllites (Carboniferous?)
7 limestones and shales of the northern sedimentary zone (Tethys Karakorum)
8 aplitic granites
9 basic intrusives
10 granites of southern zone, age relation doubtful

sive ligament, a predominantly granitic zone missing in the NW Karakorum and supposed to have welded the Karakorum to the Himalayan orogene.

For the total range, of which large tracts are still little known, I propose a more generalized subdivision into:

1. *A northern sedimentary zone* (Tethys Karakorum).
2. *A central metamorphic zone with a plutonic core.*
3. *A southern volcanic schist zone.*

All three units are separated by steep thrust zones, the northern ones trending northwards in the NW Karakorum, the southern ones towards the south. It is not yet known to what extent these steep thrusts, which show a marked parallelism to the regional strike, have at some time acted as strike-slip faults. The vertical component has certainly played the dominant role, rejuvenated during the youngest morphogenetic uplift of the range.

NORTHERN SEDIMENTARY ZONE

This zone, showing the lowest grade of metamorphism of the Karakorum, has preserved some of its fossils, allowing the establishment of a stratigraphical sequence from the Upper Carboniferous to the Upper Cretaceous, although with considerable gaps. Marine sediments form an important part in the build-up of the *Aghil ranges* and can be followed southeastwards into northeast Ladakh (NORIN, 1946). They outcrop along the large Siachen and upper Baltoro Glaciers, where they are interrupted by the K2 gneisses, the latter being the southeastern end of a narrow granitic and gneissic zone extending far to the northwest within the Palaeozoic sediments (GATTINGER, 1961; DESIO, 1936, 1955). After a considerable gap in the region of the upper Shimshal (headwaters of the Hunza) for which little information has been available, the northern zone is known again in the NW Karakorum (SCHNEIDER, 1957, 1960), from where it follows along the Hindu-Kush into Afghanistan.

The sediments begin with a thick sequence of black shales (pre-Upper Carboniferous) followed by shales and limestones (Permo-Carboniferous), with limestones and dolomites above (Triassic-Jurassic). Clastic rocks and volcanics are present only in the southeast, and, except for the Upper Cretaceous, are apparantly missing in the NW Karakorum.

The black shales are a striking feature in the northern Karakorum landscape; their smooth black forms contrast with the wild granitic and gneissic rocks of the Central zone, which in the northwest is generally steeply thrust over the shales. Limited mostly by tectonic contacts, only their minimum thickness is known, given by SCHNEIDER for the NW Karakorum as much over 1000 m. He calls them the *Pasu shales* and compares them with the *Fenestella* shales of the Himalayas. DESIO (1960) found as early as 1929 similar black shales and schists of the Upper Baltoro bearing *Fenestella* of Carboniferous age. In the Shaksgam and Aghil Ranges the black shales contain some grey and black limestones, conglomeratic horizons, and reddish schists (DESIO, 1960). The increase in clastic sediments may indicate a Gondwana influence, which is very marked in the SE Karakorum and its extension in northern Ladakh (NORIN, 1946).

Above the black shales, usually with tectonic contacts, follow *limestones and marl formations* with phyllites and some quartzites at their base. HAYDEN discovered in these horizons in the upper Hunza Valley a Permo-Carboniferous fauna (HAYDEN, 1915), and SCHNEIDER was able to discover a similar fauna in marls and limestones of the northern border of the Batura Glacier (SCHNEIDER, 1957). In the Aghil ranges of the Middle Karakorum this formation is highly fossiliferous (DESIO, 1936; WYSS, 1940). Black limestones and marls with a rich brachiopod fauna are here overlain by grey Permian *Fusulina* limestones (DESIO, 1960). They are followed by an impressing carbonate sequence. Beginning with shales, quartzites and some calcareous conglomerates at the base, the huge section of limestones and dolomites is regarded mostly as Trias-Jurassic, though the fossil evidence is poor (Triassic megalodonts and Jurassic belemnites).

As already mentioned, the *Gondwana facies* encroaches on the SE Karakorum and influences the sedimentation of the northern zone. From the SE Aghil ranges NORIN (1946) describes the *Horpa-Tso* formation, lying between the *Fenestella* shales and the Permian and consisting of a surprising thickness (2000 m) of greyish black silts and mudstones, with pebbles of porphyrite, basalts, quartz, slates, limestones, cherts, granites and gneisses. Frequent diabase volcanics occur at the base of the formation. Some of the silts are clearly varved, and the mudstones often contain carbonized material. The overlying Permian shows also a Gondwana facies with a *Gangamopteris* flora. NORIN, who has seen the agglomeratic slates in Kashmir (which are not true agglomerates), correlates the Horpa-Tso formation with these.

Mesozoic deposits up to the Upper Cretaceous follow conformably above the Permian. The Trias, though lying conformably on the Permian, begins with a conglomerate, as in the Middle Karakorum. A thick Middle Trias with megalodon horizons contains again some conglomerates and red nodulous limestones of Carnian age. This latter fact is most important in relation to some of the Tibetan exotic blocks. The *Jurassic*

is continental to shallow marine with plant remains in the Middle Jurassic and may be related to an Angara facies. The *Lower Cretaceous* shows a calcareous development of Urgonian type. A marked change related to orogenic movements can be noted in the *Upper Cretaceous* rocks, with its Flysch deposits reminiscent of the Indus Flysch with ophiolitic intercalations (see under Tibetan Himalayas of the Punjab, p. 104).

Of particular interest are the Upper Cretaceous-Lower Tertiary calc-dolomite conglomerates. In the northwestern Karakorum HAYDEN (1915) observed in the upper Hunza Valley (north of the Batura Glacier) large blocks of a peculiar *sedimentary conglomerate*, which he correlated with the *Reshun conglomerate* of Chitral (SW Hindu-Kush). SCHNEIDER was able to find the outcrops of this conglomerate in the Shanoz ridge nearby, and gives a sketch of the location (Fig. 9). Here the conglomerate consists exclusively of limestone and some dolomite components, with a fine-grained quartz-carbonate sandstone as matrix. The latter can increase upwards forming beds several metres thick. Similar conglomerates were observed by DE TERRA (1932) in connection with the Upper Cretaceous of the eastern Karakorum, with pebbles of Senonian and Danian limestones. Here too crystalline components are completely lacking. This conglomerate can be transgressive on folded Triassic and Jurassic sediments and grades upwards into terrestrial deposits. The latter were also folded and faulted and then transgressed by younger continental Tertiary. It is most likely that DE TERRA's conglomerates of the eastern Karakorum correspond to the Reshun (HAYDEN, 1915) and Batura conglomerates (SCHNEIDER, 1957). In all these monotonous conglomerates limestones and dolomites of Mesozoic age, including Upper Cretaceous, form the exclusive components. Crystalline components are completely missing, in striking contrast to the basal conglomerates of Middle Cretaceous age of the Indus Flysch. Crystalline sources must have been covered or out of reach during the strong but probably more local erosive activities at the end of the Cretaceous.

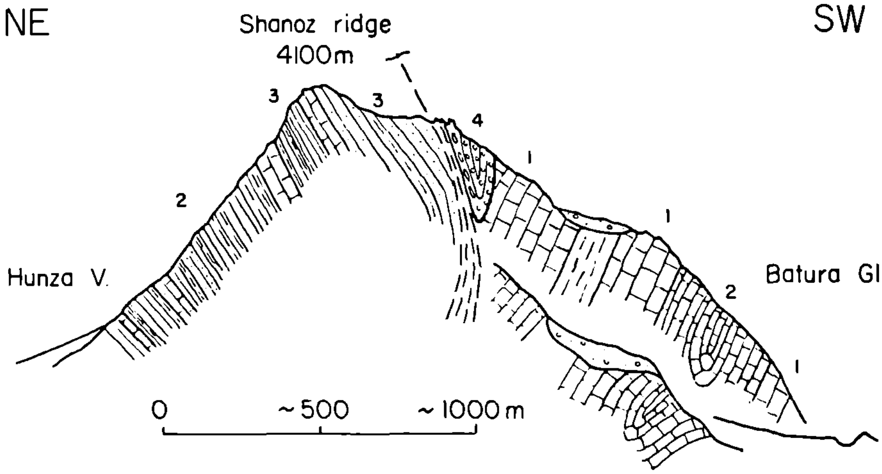


Fig. 9 *Limestone conglomerates in the Shanoz ridge,* Batura glacier, NW Karakorum; redrawn after H. J. SCHNEIDER (1957)

1 thick-bedded limestones (*Fusulina* limestones of Hayden)
2 shales and marly limestones (Permian?)
3 limestones and siliceous sandstones (Middle Triassic)
4 limestone conglomerates (post Upper Cretaceous)

A most interesting fact is that most of these peculiar calc-conglomerates have undergone subsequent tectonic deformations. SCHNEIDER reports and pictures some schistose conglomerates with strongly elongated (stretched) pebbles (SCHNEIDER, 1957). There is no doubt that these deformations correspond to a younger Alpine orogenic phase superimposed on the older structural phases of the Karakorum. Recently GATTINGER (1961) described similar conglomerates from his coloured formation discovered in the Gasherbrum mountain group in the Upper Baltoro Glacier. They may correspond to the conglomerate blocks, already mentioned by DESIO (1936) and DYHRENFURTH (1939), from the moraines of the Baltoro Glacier. The Gasherbrum coloured formation consists mainly of grey conglomerates at the base, followed by red conglomerates alternating with red and yellowish mottled sandy shales and sandstones. It transgresses the intensely folded limestones and black schists. Similar to the Batura

conglomerates of SCHNEIDER, they were subject to the latest Alpine folding phases. Here again, no trace of crystalline components was observed. The rather small pebbles (up to 4 cm) are badly rounded and consist of dark and light coloured limestones and dolomites. They seem to be derived mostly from a local source. This fact does not, however, explain the exclusively carbonate components in all the widespread localities of the Karakorum where these young conglomerates have so far been found. The many problems related to these surprising sedimentary conglomerates are a stimulating research object for future exploration.

The northern sedimentary zone is intruded by *young granites and their related dyke systems. Young* means here late to post orogenic, since the igneous rocks are not tectonically affected, and therefore younger, for instance, than the stretching and stressing of the above-mentioned conglomerates of latest Cretaceous to early Tertiary age. The granites cut discordantly all northern sediments, without any marked contact effects. Their contact zone is sharp. In the NW Karakorum there occurs, according to SCHNEIDER (1957), a lamprophyric dyke system, believed by him to be the oldest of this young suite. It is followed by quartz trachytes, also mostly in dyke form. Still younger are coarse, somewhat porphyric granites, which form plugs, and contain frequent inclusions of the above mentioned dyke rocks. A still later pneumatolitic phase has impregnated these granites locally with molybdenum, together with epidote and fluorite, and shows a marked albitization.

CENTRAL METAMORPHIC ZONE AND ITS PLUTONIC CORE

The oldest rocks in this zone, and probably of the whole Karakorum, are *banded biotite-hornblende gneisses.* They are well exposed in the Hunza Valley, where SCHNEIDER (1957) measured the oldest structural 'b' axes, plunging gently to the northwest. The banding of the gneisses is accentuated by acid layers of pegmatitic composition, which represent an incipient granitization. In the Hunza Valley younger aplite granite veins, lenses, layers, and small masses cut through the banded gneisses, marking the spectacular exposures in the Hunza Gorge above Saret. Similar gneisses in the Middle Karakorum are included by DESIO (1960) in his Mustagh gneiss, with biotite-hornblende gneisses, granite gneisses and intercalated biotite schists.

The K2 (Mt. Godwin Austen), the second highest mountain of the world and the highest peak of the Karakorum, consists of the K2 gneiss of DESIO (1960). It is a biotite-muscovite augen gneiss, with large plagioclases. Intercalted are more psammitic gneisses and biotite schists. Of special interest are calc schists and crystalline limestones, which, however, seem to be different from the marble series to be discussed with the more southerly schistose zone (Fig. 10). According to GATTINGER (1961) the K2 granite gneisses belong to a northern granite and gneiss belt separated from the Central Crystalline Zone.

In the deeper and southern sections the banded gneisses can imperceptibly grade by increasing granitization into the granodiorites and granites of the Central Zone. The granitic material of the banded gneisses increases, the contacts become diffuse, nebulitic-migmatitic masses occur and finally there are homogenous granites, Baltoro granite (Ph. 1, 2, 3). Northwards, and probably higher in the granitized sequence the contact of granites with schists is irregular but sharp, and the latter are frequently included as xenoliths.

GATTINGER (1961) discusses the granitization of schists in the deepest outcrops of the Shigar Valley (Central Karakorum). From the lowest granitic gneisses, passing through augen gneisses, banded gneisses and mixed gneisses one reaches the upper para-schists. The granitization is here older than the intrusion of the axial granites, since the latter, in form of dykes and stocks, cut through the already granitized and syngenetically folded rocks. GATTINGER suggests that the original schists are not younger than Middle Palaeozoic, if a Carboniferous age is assumed for the black (Fenestella) schists, the base of the Tethys sediments in the Karakorum. A much older age, even Precambrian would, however, not be excluded. The granitization leading to the granite gneisses is believed to be syngenetic and related to young Hercynian phases, while the later granite intrusions are supposed to be Alpine. A certain divergence in the structural alignment is mentioned by GATTINGER, and is compared with the results of the structural analysis by SCHNEIDER. In the central Karakorum an older E-W alignment, to which the granitized crystalline seems related (Hercynian), differs from the more ESE-WNW alignment of the Alpine granite intrusions. In my opinion the available facts are not very convincing. There is no doubt that the above mentioned granitization is syngenetic and that the cross-cutting granites are post-, or at least late orogenic. But is it actually necessary to separate the two phases by 150 million years? Examples from the Himalayas to be discussed later, such as Nanga Parbat, clearly show that a syngenetic granitization is frequently followed by post-orogenic granitic intrusions, cutting sharply through the existing gneisses which often have been intensely folded. The granites are, however, nothing but a *latest phase of completeley mobilized material*, intruded from deeper levels into the upper horizons, and seem to belong to the same major

orogeny. It remains to be seen how much of the Karakorum granitization and intrusions is actually related to one and the same orogeny, or whether, as suggested by GATTINGER, widely separated phases are involved.

The central granites and granodiorites are very widespread in the axial zone of the whole Karakorum. NORIN (1946) gives the following approximate distribution for the eastern Karakorum: biotite granite, 50%; biotite-hornblende granites, 30%, and biotite-muscovite granites, 20%. The alkali feldspars dominate with microcline and orthoclases in about the same amount. This may not say much, since microclines without quadrille structure can hardly be distinguished from orthoclase without detailed investigations. From the northern Central Karakorum AUDEN (1935, 1938) mentions hornblende-biotite granites rich in xenoliths of epidiorites, quartzites and slates. From the Baltoro Glacier (Central Karakorum) DESIO (1936, 1960) describes the Baltoro granite as medium-grained biotite granite (Ph. 1, 2, 3) SCHNEIDER (1957) shows that hornblende-biotite granites (granodiorites) are the predominant rock of the NW Karakorum. They are, however, not homogeneous and can vary from hornblende diorites to hornblende-free biotite granites. In general hornblende seems a highly characteristic constituent of the Karakorum granites, and distinguishes them from most of the Himalayan granite types. As we will see later, the Transhimalayan granites in the Kailas Range, an eastern continuation of part of the Karakorum, are also characteristically a hornblende-biotite type.

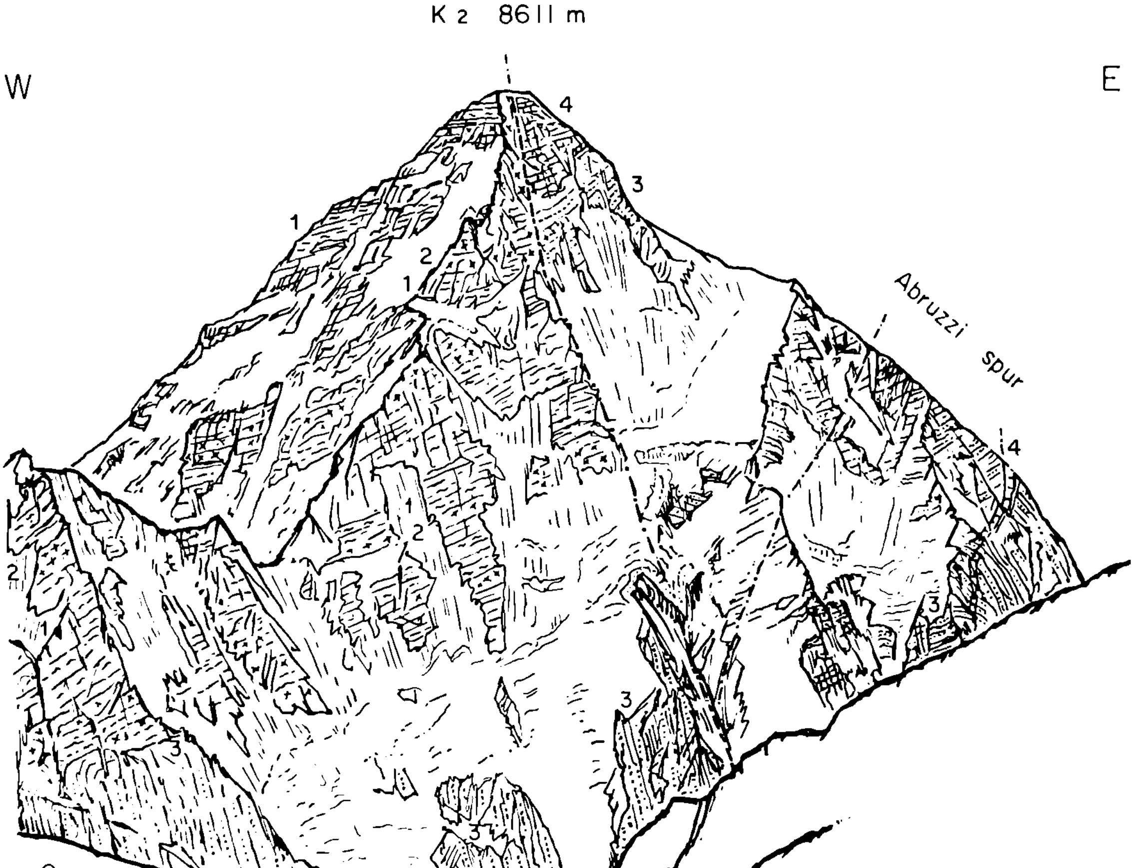


Fig. 10 *The geology of K2 (Mt. Godwin Austen)* Central Karakorum; drawn after photographs of G. DYHRENFURTH and V. SELLA. Geology after A. DESIO (1960)

1 muscovite biotite gneisses, partly developed as augen gneisses . . . .
2 granitic and pegmatitic layers
3 hornblende gneisses of Falchan-Kangri type (DESIO)
4 calc schists and marble bands
note three fault zones —·—·—·—

Together with the gneisses, but more widespread towards the southern part of the central zone which contains the granitic-granodioritic core, occur *crystalline schists*. These high-grade metamorphic schists are still included in the central zone, intimately related to the gneisses. The most striking aspect of these schistose zones are the widespread *marble bands*, which are certainly one of the most conspicuous features of the Karakorum (Ph. 4, 5). The marbles can be followed from the eastern central to the western Karakorum and the author has seen very similar outstanding marbles in the Hindu-Kush of Afghanistan. They are highly metamorphosed in the western Karakorum, and become less metamorphic towards the southeast so that fossils can be recognized.

In the NW Karakorum SCHNEIDER (1957, 1960) observed the marble formations immediately south of the axial zone. Here, in the Toltar group, they seem to have their maximal development, with exposures 1000 m thick. Imbrications and tight isoclinal folding may, however, be responsible for this excessive thickness. The white marbles are very coarse, with calcites of 2 cm diameter, and a content of large phlogopite and graphite scales. The marbles are intercalated in biotite schists, amphibolites, garnet gneisses and quartzites. They decrease towards the ENE by an increase of the interfingering schists and amphibolites and cross the Hunza Valley more reduced. They are cut by younger aplite granites which contain large angular xenoliths of considerable size (Fig. 11). The contact with the central granodiorites is rarely exposed. SCHNEIDER found that the south-vergent folding and imbrication of the marble series was formed prior to the emplacement of the axial granodiorite.

In the Central Karakorum similar marble zones have long been known (DAINELLI, 1934; DESIO, 1936; DYHRENFURTH, 1939; AUDEN, 1935, 1938). Here they are much less recrystallized and contain Permo-Carboniferous fusulinids. DESIO and CITA (1955) reported recently from the Baltoro basin new finds of Permian *Fusulina* limestones, collected, however, from moraines derived from the Upper Baltoro. The limestones could correspond to the Permo-Carboniferous of the northern sedimentary zones, and a connection of the latter with the central zones seems indicated in the Middle Karakorum (Baltoro region). GATTINGER (1961) believes that the sediments of the central

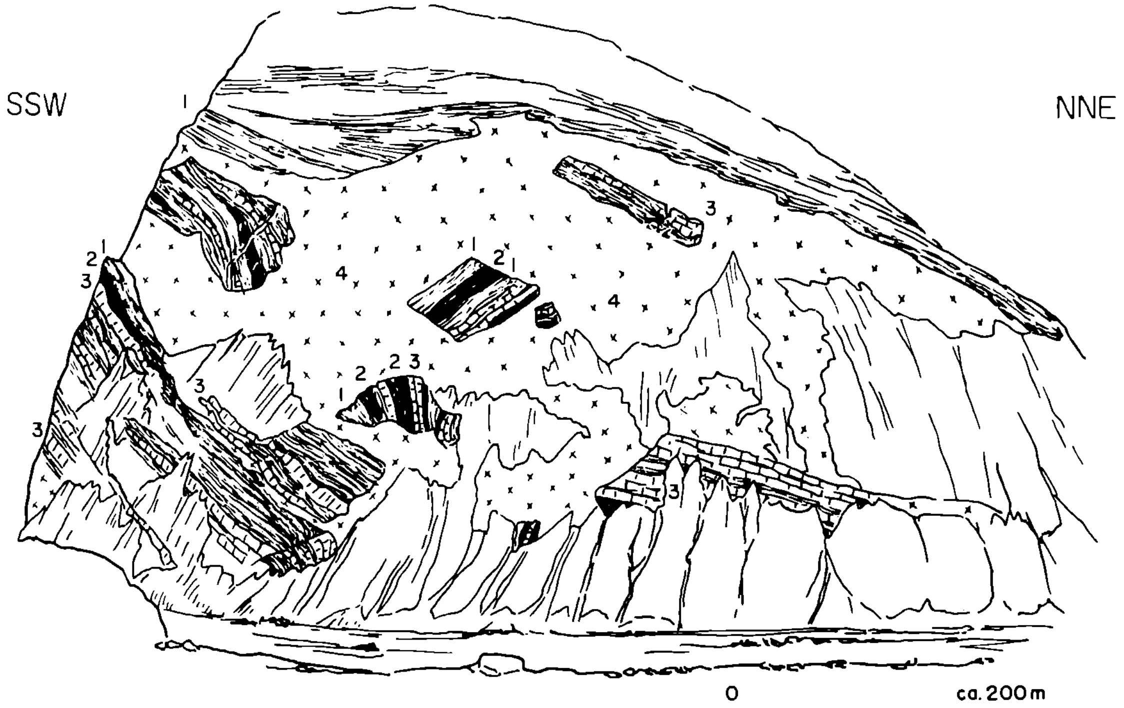


Fig. 11 *Young aplite granite intruding the marble amphibolite series in the southern part of the Central Zone.* Shispar glacier. NW Karakorum; redrawn after H. J. SCHNEIDER (1957)

1 schists
2 amphibolites
3 marbles
4 post orogenic aplite granite
note large angular xenolites, rotated from their original position

zone in the Baltoro and the Siachen Glacier regions as well as some remnants east and west of Askole, are thrust from the northern sedimentary zone over the central zone. They are fluidly folded and their metamorphism is higher in comparison to the northern area. With this new interpretation one may question whether the marble zones described by SCHNEIDER from the northwestern Karakorum can be safely correlated with the Baltoro sediments.

Towards the ESE, between Chalt and Nomal, north of Gilgit, and again further east in the over 7000 m high Rakaposhi-Diran Range, occur large masses of augite-porphyrite (Rakaposhi core) diabases and gabbros (S Chalt) with associated agglomerates and other clastic rocks of the Chalt type. In this southern region the metamorphism has regionally increased and towards Gilgit the basic rocks, often as amphibolites, are intruded by younger granites and granodiorites.

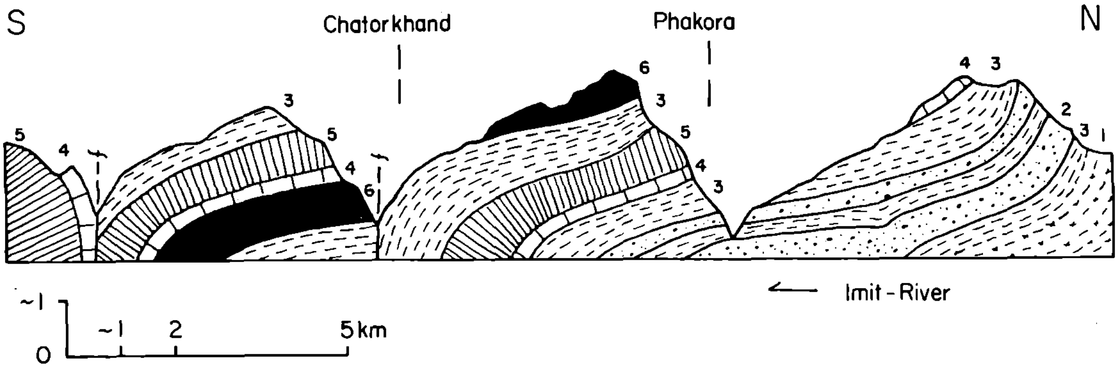


Fig. 12 *Schematic cross section through the Chalt series.* Ishkuman Valley, the border zone between Karakorum and Hindu-Kush; redrawn after H. J. SCHNEIDER (1960)

1 gneisses
2 greywacke series
3 slates and phyllites
4 marble bands
5 tuffaceous green schists
6 basic and ultrabasic flows and intrusions

SOUTHERN VOLCANIC SCHISTS

South of the central zone, and divided from it by steep north-dipping thrusts there follows a very complex zone of detrital rocks and volcanics, intensely folded and faulted and characterized by a low-grade metamorphism. Its folds are isoclinally directed southwards like the various steep thrusts. Its southern limit in the NW Karakorum is formed by the Rakaposhi Range. SCHNEIDER (1957, 1960) describes this zone under the name of *Chalt schists,* and GATTINGER (1961) as *Schuppenzone.* In the cross section of the Ishkuman Valley, the border zone between NW Karakorum and eastern Hindu-Kush, a less disturbed section of the Chalt schists is well exposed (Fig. 12). The base is formed by dark grey phyllitic schists. Upwards they grade into quartzites followed by greywackes and conglomerates. A 20-40 m thick marble, underlain by thin phyllites, forms the base of the volcanic deposits. Tuff and agglomerates with intercalated lenses and layers of spilitic diabases represent the 1000-2000 m thick volcanites, covered again by thin marbles and phyllites. SCHNEIDER reports also some serpentine lenses in the Naltar Valley (NW Gilgit).

This metamorphic and intruded zone leads directly into the crystalline masses of the Nanga Parbat, the striking culmination of the western Himalayan syntaxis. From what is known so far, particularly through the investigations of SCHNEIDER, *the volcanic and clastic southern belt of the Karakorum is actually a transition zone between Karakorum and Himalayas.* Its relation with the regional Indus suture line will be discussed later.

From the Chalt region the volcanics can be traced southeastwards to the Chogo Lungma Glacier. Further on its continuation is still obscure. Possibly part of the Shigar zone and the Falchan Kangri series of DESIO (1960) in the Central Karakorum represent the clastic part of this southern zone, with reduced volcanics. GATTINGER introduces here his south border crystalline. East of the sharp Indus River bend and south of Haramosh Peak a wide granitic zone is interpreted as an intermediate belt between the southernmost Karakorum and the northern Himalaya, separated as his *intrusive ligament* from the *Schuppenzone* and the south border crystalline.

In the southeastern Karakorum corresponding formations have so far not been recognized with certainty. DE TERRA (1932), however, describes

clastic and volcanic metamorphics from the upper Shyok Valley, and from the same locality (village of Shyok) WYSS (1940) collected an Uralian fauna, confirming an Upper Palaeozoic age for part of this section. The structural aspect, with steep folds and imbrications is similar to the compressed and south-vergent tectonics of the NW Karakorum.

Southeast of Shyok, along the Pangong Tso, GATTINGER sees an eastwards continuation of his Schuppenzone, following south of the central gneisses and granites of the *Tshang Tshenmo Range,* although the wide alluvial highland along the elongated lakes masks much of the outcrops. The relatively sharp change from the general ESE strike into the E-W direction expressed in the Tshang Tshenmo Range is still little understood (Pl. I A and B).

In the eastern Hindu-Kush HAYDEN (1915) observed the clastic and volcanic formations which continue from the NW Karakorum over the Ishkuman and Yasin Valley into the Chitral region. He found a marked transgression of Lower to Middle Cretaceous over the volcanics. The section of the Yasin region has recently been investigated by DESIO (1959), who was able to confirm HAYDEN's observations. The basic volcanics of Cretaceous age in the Yasin section should not be confused with the older volcanics of probable Upper Palaeozoic to Lower Mesozoic (Triassic) age (Gondwana Traps).

STRUCTURES OF THE KARAKORUM

The imposing aspect of the Karakorum is the result of very young *morphogenetic movements,* which are supposed to have acted along marked ESE-WNW fault zones, uplifting the central part to its present heights. Generally the Karakorum is regarded as an important link between a Hercynian Pamir and an Alpine Himalaya. These somewhat simple and dogmatic views are based on still rather scattered evidence which allows the squeezing of facts into a rigid scheme. We know that the Pamir region has been affected by Alpine orogenies. Its present spectacular mass is of a very young date. Certainly multiple tectonic phases have played an important role, whereas the so often stressed Hercynian orogenies seem to have had a rather minor effect. This point is evident again in the Karakorum. Discrepancies between pre-Alpine and Alpine tectonics are reported (SCHNEIDER, 1957; GATTINGER, 1961) but are not easily recognizable, a fact still more apparent in the Himalayas.

Orogenic movements have been active and have been reactivated during various phases, still difficult to date, since, like the last Alpine phase, they have wandered mostly from north to south. The Alpine orogenies in the Karakorum have certainly begun in the north in the Middle to Upper Cretaceous, were active in the Central part at the Cretaceous-Tertiary boundary, and continued in the south during the early Tertiary. The morphogenetic phase began much later and, based on the present morphological aspect of the range, is still active. SCHNEIDER considers the uplift since early Tertiary to be 12,000 m. It is surprising to note that in spite of such large vertical movements, probably mostly very young, one sees enormous steep rock walls, but no marked steps in the deep valleys. This fact, characteristic also for the Himalayas with its antecedent rivers cutting indifferently through the whole range, is a matter of special interest and will be discssed later.

In the northwest, the Karakorum is a typically two-sided orogene (Fig. 8). The northern sedimentary zone is clearly north vergent, and at the contact the central crystalline masses are steeply thrust northwards. On the south side, a south-directed tectonic style is characteristic, with steep thrusts and isoclinal folding (SCHNEIDER, 1957). In the southeast Karakorum, where the whole range opens and widens eastwards, and turns from a southeast direction into a more E-W strike, southwards-directed folds have been observed in the northern ranges (DE TERRA, 1932). Recently GATTINGER (1961) has shown that the northern sedimentary zone of the Central Karakorum is clearly south vergent, and he even indicates thrusts of northern elements over the central crystalline zone, with horizontal displacements up to 50 km. This would imply that the whole sedimentary mass of the Baltoro and Siachen Glaciers, conspicuously metamorphosed and subject to a particularly plastic folding, would belong to this northern thrust mass. It may be questioned whether this interpretation is universally acceptable. If the thrusting is very young, then the relatively high-grade regional metamorphism of the sediments is difficult to explain. Earlier thrusting, prior to a regional metamorphism of the Central range must be assumed, and GATTINGER places this thrust movement before the intrusion of the axial granite. So far it seems that only the Palaeozoic part of the northern sedimentary zone is involved in these thrust masses. It should be ascertained if facies differences do exist between the thrust Palaeozoic and the similar deposits in the north (see also DESIO, 1963).

The distinct south-vergence of the northern region can be observed northwestwards as far as the Hispar Pass. From here to the Northwest Karakorum a rapid change from southwards-directed to north-vergent structures must occur.

The magmatic activity of the Karakorum is related to its orogenic phases. The earlier pre-Upper Cretaceous Ladakh granite, in the continuation of the southern East Karakorum, and the pre-Cretaceous trap-like volcanics, represent facts

from an earlier Palaeozoic history, still difficult to unravel. The Cretaceous basic vulcanism can well be compared to an initial orogenic phase of Alpine type. Since it was active mostly in the southern border of the range, it seems more related to the Himalayas and the important suture line of the upper Indus Valley (see later). The synorogenic to late orogenic central granites and granodiorites are connected to the main orogenic phase in the central part, which occured at the Mesozoic-Tertiary limit. The late to post-orogenic aplitic granites have hardly been disturbed by the main orogeny, and must be of Oligocene or younger age. If we compare them to the central granodiorites with their migmatic border zones, they must have been intrusive into a higher level of the mountain range, which may indicate that substantial vertical movements had already preceded the intrusion of this youngest migmatic phase.

SCHNEIDER has tried, by careful structural analysis, to unravel the structural history of the NW Karakorum (SCHNEIDER, 1957). His results show a remarkable constancy of the detailed structural elements within a main zone, even if measured in lithologically different material. They are not necessarily conformable to the steep thrusting which borders the various zones and is particularly well expressed in the western Karakorum, where the influence of the Himalayan syntaxis is strongly felt. The bending of the western Karakorum from an ESE-WNW into an E-W strike, and, in its continuation as the NE-SW-directed Hindu-Kush, is the reflection of the syntaxis. The higher grade of metamorphism in this region is similarly related. Still puzzling, and certainly one of the most fascinating future studies, are the connections of the N-S-striking Nanga Parbat elements of the Himalayas with the here almost E-W-striking Karakorum. The key area lies in the eastern Rakaposhi Range, south of the Chogo Lungma Glacier, where geological information is so far missing.

CHAPTER V

PUNJAB HIMALAYAS

The Punjab Himalayas cover the mountain section from the Indus in the west to the Sutlej in the east. This stretch of approximately 550 km was originally, i.e. before the division of India in 1947, mostly in the Punjab territory. The present Indian Punjab covers only its easternmost part, and in the discussion of the Punjab Himalayas we include also the Pakistan and the Indian Kashmir regions.

The Punjab Himalayas with Kashmir represent the best known section of the Himalayas, although they cover one of the most complicated regions of the 2400 km long mountain range. They include the extraordinary western Himalayan syntaxis, and reach northwards to the southern border of the previously discussed Karakorum. It is an area famous for its fossiliferous formations, which, in contrast to the more eastern segments of the Himalayas, cross the High Himalayas and are developed in the Lower Himalayas of Kashmir.

Favourable climate, easy access, and a complete stratigraphy are the reasons for the early start of geological work in the Punjab Himalayas, particularly in the Kashmir Valley. The first investigations were carried out by LYDEKKER in the second half of the 19th century (LYDEKKER, 1883). Covering a large unknown area his results were accordingly vague, and it was only after the intensive research by MIDDLEMISS (1910, 1913) that a more detailed and reliable stratigraphy was available on which WADIA could base his comprehensive studies of the Kashmir region. We owe much of what is known of the Punjab Himalayan geology to WADIA's research and compilations. His classical *Geology of India*, first published in 1919, with subsequent editions in 1939, 1953 and 1957, contains a wealth of information on the Himalayan range and particularly on the Punjab section (see also WADIA, 1928, 1929, 1930, 1931, 1934).

SUB-HIMALAYAS OF THE PUNJAB

Under Sub-Himalayas we understand the low foothills, consisting predominantly of Tertiary formations, which border—along the so-called *Main Boundary Fault*—the older rocks of the Lower Himalayas. Southwards the Sub-Himalayan structures are limited by the Indus-Ganges-Brahmaputra alluvial deposits. The Sub-Himalayan sections of the Punjab are well known, partly through the occurence of oil deposits. This special interest has justified some modern investigations, which have not always produced results in line with the classical views.

The most characteristic and widespread rock formation of the Sub-Himalayas are the *Siwaliks*, not only in the Punjab section but all along the 2400 km long foothill belt. Named from the Siwalik Hills near Hardware, where the first world-famous vertebrate fossils were discovered (MEDLICOTT, 1864), they represent mostly freshwater Molasse-like deposits, originating from the rising Himalayas, and embrace the Middle Miocene to Lower Pleistocene. The Upper Siwaliks straddle the Plio-Pleistocene boundary, which, as we will see, is still somewhat controversial and involves the history of the earliest Himalayan glaciation. Below the Siwaliks lie the Murrees, outcropping only in the western Sub-Himalayas but forming a belt of steeply folded beds, more than 30 km wide. They range from the Lower to the Middle Miocene. Pre-Murree rocks have been found in borings and do outcrop in the Salt Range, as already mentioned. The only pre-Murree outcrops within the Sub-Himalayan Tertiary belt form most conspicuous Palaeozoic limestone mountains in the Jammu area, 25 km to the south of the Main Boundary Fault. This most interesting occurence will be discussed under the Lower Himalayas (p.59).

The best and, at least for the lower formations, the thickest deposits of Murrees and Siwaliks occur in the Punjab section of the Himalayas. The relatively little-disturbed upper horizons are well exposed in the Potwar basin, situated between the Salt Range and the Hazara foothills of the Lower Himalayas, and possibly representing a locally uplifted part of the Indo-Gangetic basin involved in the youngest Himalayan orogenic phase. Detailed investigations have recently been carried out in this basin by GILL, who also

studied sections of the Siwaliks on the eastern side of the Punjab Sub-Himalayas (GILL, 1951).

The nature of the detrital, synorogenic to late-orogenic deposits is responsible for the great difficulties in solving the stratigraphy of the Siwaliks. In spite of the spectacular vertebrate faunas in some Siwalik horizons, much remains uncertain to the present day. Lateral facies changes and heterochronous lithological horizons are more frequent than was in fact evident from the older more generalized investigations. However, a prevalence of certain key horizons allows a regional zoning all along the foothills. These characters of the Siwaliks of the Punjab Sub-Himalayas will be discussed in more detail in order to facilitate correlation with the Siwalik regions of the more eastern Sub-Himalayas.

Murrees

The base of the Murrees is not exposed in the Punjab Sub-Himalayas. Outcrops in the Salt Range have shown a transgression of the Lower Murrees onto the Lower Eocene Laki beds, with intervening gypsum and some saline red beds. Middle to Upper Eocene as well as Oligocene are missing, and throughout the whole of the Punjab region no Oligocene has been recognized.

The pre-Miocene marine Tertiary cycles ended before the deposition of the brackish to fluviatile freshwater Murrees. The change is characterized by evaporitic intercalations with no marked unconformity other than a local development of conglomerates with reworked Eocene nummulites. Where fully developed the Murrees are nearly 3000 m thick. On lithological grounds they can be divided into Lower and Upper Murrees. For the whole section a dark-red to purple colour is characteristic for the clays and silts, while the sandstones are deep-red and brown. The *Lower Murrees* contain thick sections of red shales, silts and clays, with ridge-forming dark-red sandstones towards the top. The silts and shales are often contorted and have frequent calcite veins; nodular clays are intercalated with purple shales. The *Upper Murrees*, with the red colouring still dominant, are somewhat more arenaceous and begin to resemble the coarser brownish-grey sandstone layers which form the base of the Lower Siwaliks. Compared to the Lower Murrees, the Upper Murrees are generally less disturbed, and their structures align themselves more to those of the Siwaliks. Faunal evidence for the age of the Murrees is rare—the vertebrate and plant remains reveal a *Lower to Middle Miocene age.*

Except for some coarser sandstones and very locally developed basal conglomerates, the Murrees are very fine-grained detrital deposits, derived from a low-relief hinterland. A notable feature is the iron staining responsible for their typical red colouration. A Himalayan source for the Murrees seems most unlikely, and some authors believe the Murrees to have originated from sediments related to the iron-bearing Puranas of the Indian shield. This would indicate a southern source, in marked contrast to the northern source of the younger Siwaliks (WADIA, 1953).

The Murrees of the Potwar basin can be followed around the western Himalayan syntaxis into the foothills of the western Punjab Sub-Himalayas. They form a 40 km wide band where they cross the Jhelum River, and thin out rapidly southeastwards towards the Simla foothills. GILL's investigations NW of Simla (1951) leave some doubts regarding the correlation of his Infra Nahan red shale zone with part of the Murrees; they have been tentatively correlated with the Kausali beds of the Simla area. Generally, the equivalents of the eastwards-disappearing Murrees in the NW Simla area, at the eastern limit of the Punjab Himalayas, are the Dagshai formation and the overlying Kausali red beds, mapped 100 years ago with surprising accuracy by MEDLICOTT (1864). The boundary of the Upper Murree equivalent—the Kausalis (or Infra Nahans of GILL)—with the overlying Siwaliks is still uncertain, and certainly transitional.

Phot. 1 *The granite cliffs of Paju,* Lower Baltoro Glacier. The Baltoro granite exposes vertical and horizontal jointing (phot. V. Sella)

Phot. 2 *The wild Tramgo Towers,* Baltoro granite, Lower Baltoro Glacier (phot. V. Sella)

Phot. 3 *Baltoro granite mountain between Dunghe Glacier* (left) *and Bial Glacier* (right). Scree covered Baltoro Glacier in foreground. (View to N.) Note excellent vertical jointing and flat 'bedding' in the granite. The latter is well expressed in Mt. Biale (in the right background) (phot. V. Sella)

Phot. 4 *Marble Peak,* at Concordia, Baltoro Glacier. Note the contrast of white marbles with black phyllites and gneisses (phot. V. Sella)

Phot. 5 *The Broad Peak-Gasherbrum mountain group* in the upper Baltoro Glacier. To the left Broad Peak (8047 m) with white limestones and dark to black calc schists and phyllites. To the right Gasherbrum IV (7980 m) with white limestones. Note the banded limestones, calc schists and black phyllites forming wall of right foreground. The sediments are mostly of Permo-Carboniferous age. View towards NW (phot. V. Sella)

Phot. 6 *Large garnet in staurolite-garnet-biotite phyllite.* Kali Gorge. (1) outer border free of quartz, (2) zone of large quartz inclusions, (3) central part with small quartz and magnetite inclusions. Enl. 30×

Phot. 7 *Reaction rims of quartz between kyanite and biotite schist.* Upper Kali River (Nampa). White band = quartz, b = biotite, k = kyanite. Enl. 25×

Phot. 8 *Tight folds in quartzites with psammite gneisses.* Kali Gorge (phot. A. Heim)

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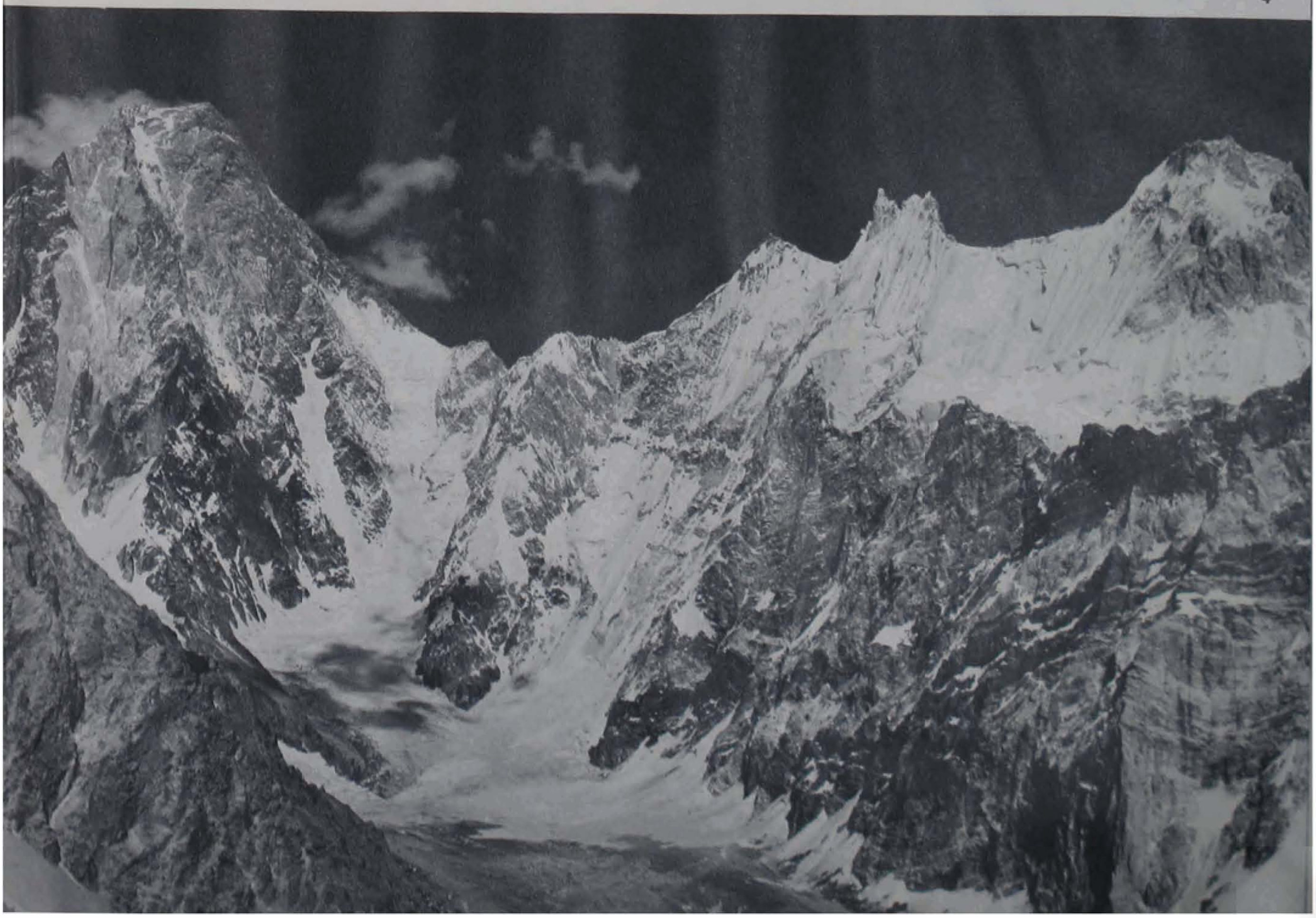

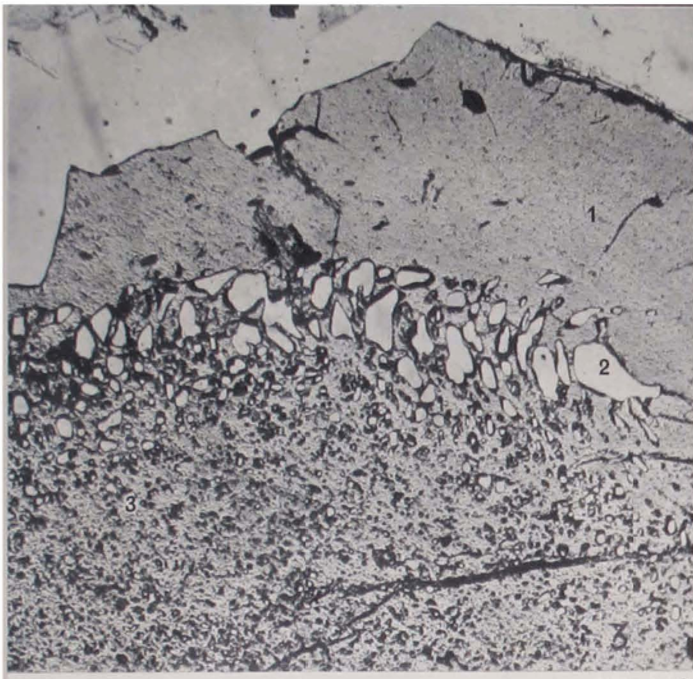

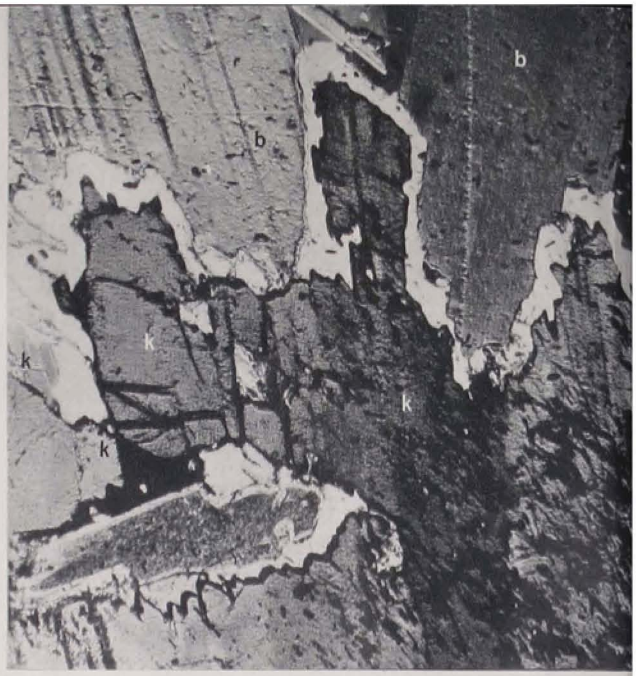

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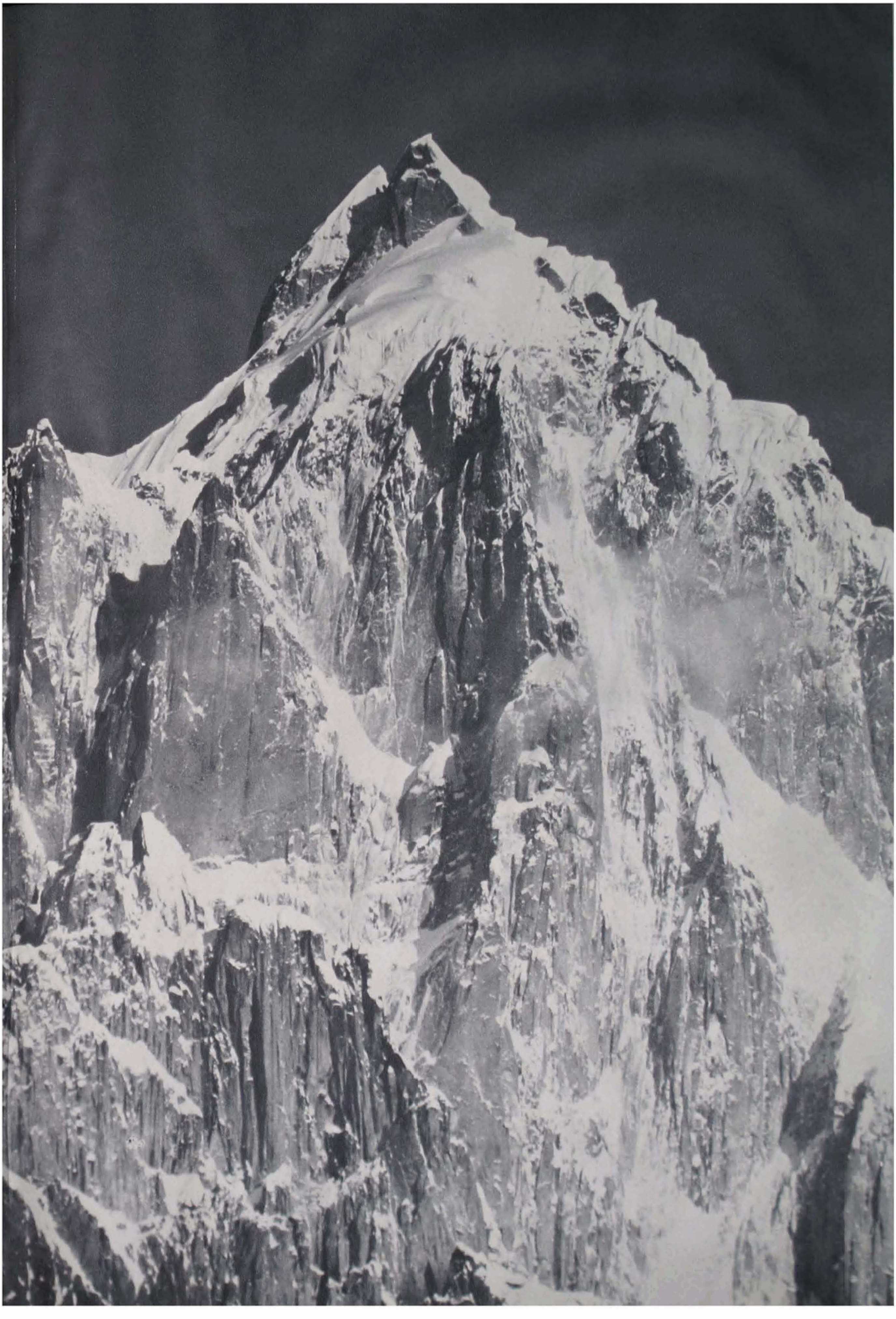

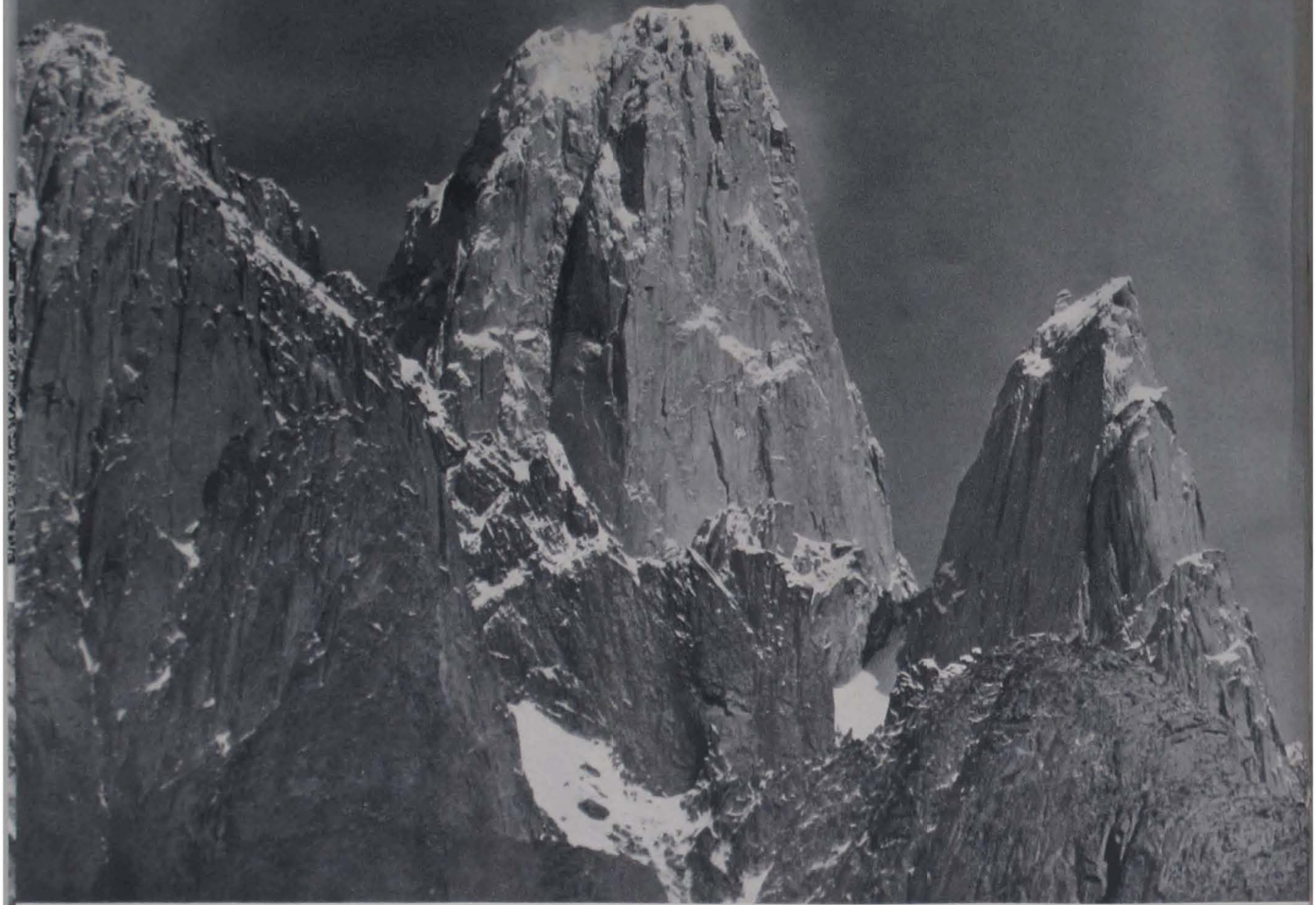

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Siwaliks

Partly on lithological and partly on faunal evidence the Siwaliks can be subdivided into three main groups, the *Lower, Middle* and *Upper Siwaliks* (Fig. 13). This three-fold division can be recognized in most of the Sub-Himalayan sections, a rather surprising fact considering the fluviatile type of deposits. In the Punjab Himalayas more local subdivisions have been applied to the Siwalik section. These subdivisions and their relation to the main sections as well as their stratigraphical setting are shown on Fig. 14, which schematically indicates the great variation in facies and thickness of the Siwaliks in the Potwar region after GILL.

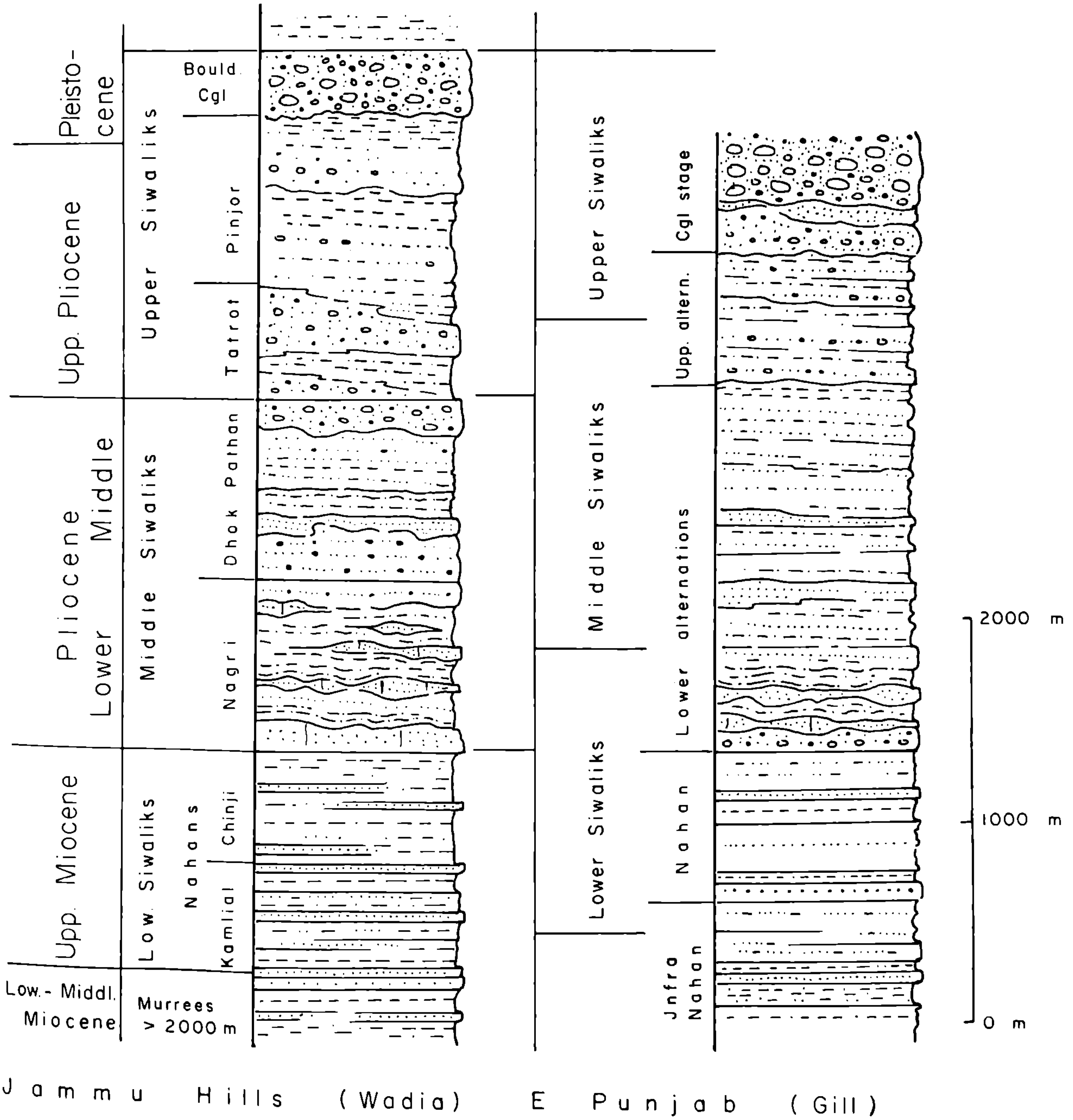


Fig. 13 *Stratigraphy and correlation of the Siwaliks in the Punjab Sub-Himalayas;* mainly compiled after D. N. WADIA (1928, 1953) and W. D. GILL (1951)

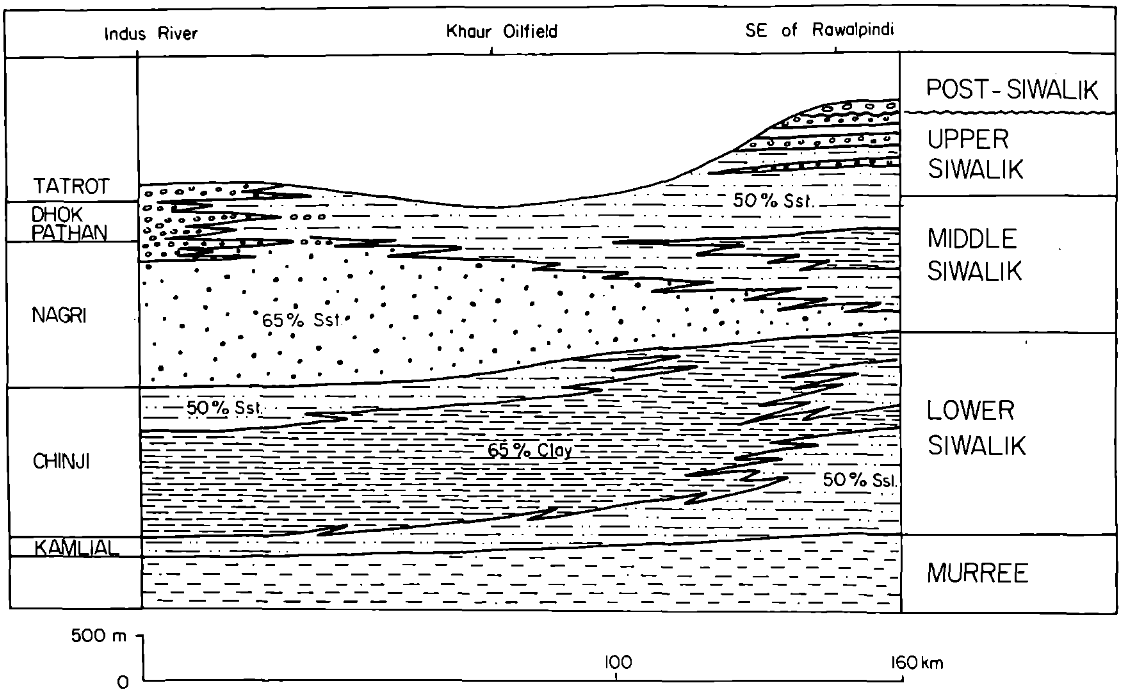


Fig. 14 *Schematic correlation and facies table of the Siwaliks in the Potwar basin.* Western Punjab Sub-Himalayas; redrawn after W. D. GILL (1951)

We have already noted that the boundary from the Murrees to the Siwaliks is gradual. Accepting a southern shield source for the clastics of the Murrees, the Himalayan influence on the Siwaliks is slight in the Miocene, increases in the Pliocene, and culminates in the Pleistocene. All this is reflected in the Siwalik sediments. We should, however, stress that so far very little is known about the actual current directions responsible for the distribution of the sediments. As we will see, the Siwalik deposits, except for their youngest conglomerate beds, are not a sequence of local interfingering fans deposited directly from the hinterland, but result from an intricate system of longitudinal rivers along which sediments travelled for often considerable distances. Recent investigations of the Alpine Molasse show quite clearly the dominant factor of sediment transport over long distances parallel to the strike of the mountains. The conspicuous longitudinal depressions within the Siwalik belts, called *Duns*, are not only the result of the constant structural trends parallel to the Himalayan range, but show also the facies changes of the Siwalik rocks from north to south, the lithology remaining surprisingly constant along the strike.

Several authors have postulated a main drainage system during Siwalik times from the Assam region parallel to the incipient mountain range into the Punjab. This Siwalik river of PILGRIM (1919) or the *Indobrahm* of PASCOE (1920) replaced the last remnant of the Eocene sea, already filled during the Murrees, and surviving only as flood plains and insignificant shallow water basins. In spite of marked local facies changes, such as outlined in the Potwar basin by GILL (1951), even the early investigators were impressed by the remarkable constancy of the Siwalik deposits on a large scale all along the Himalayan foothills. Much detailed, but certainly rewarding, work will be needed in order to be able to reconstruct the *sedimentary channels* responsible for the Siwalik deposition. Such work may eventually help to interpret the extension of Siwalik deposits into the Brahma-Ganges-Indo Plains, and an estimation of the amount of Himalayan detritus washed down into the foreland may give valuable hints about the amount of erosion. Considering the present height of the range, and the relatively shallow and narrow foreland basin (see later) the actual amount of removal may be rather small. This, however, depends on the extent of overriding of the Himalayan thrust-sheets over the Siwaliks, a problem to be tackled later.

The total thickness of the Siwaliks is estimated at over 5000 m in the Soan syncline (GILL, 1951). WADIA (1953) gives a total thickness of 5000-5500 m. This compares with 7000 m for the maximum of the Alpine Molasse, the direct equivalent of the Siwaliks. Compared to the present volume of the Alps, the total bulk of the Alpine Molasse is considerably greater than that of the Siwaliks in relation to the volume of the Himalayan mountains.

Lower Siwaliks

Lower Siwaliks, also called the *Nahans* in the eastern Punjab, are divided in the Potwar basin into a lower *Kamlial* section and an upper *Chinji* section, a subdivision adopted from the Salt Range-Attok region. The Kamlial consists of dark-grey to reddish brown sandstones overlain by dark crimson-red siltstones and shales. Some authors have placed the Kamlials into the Upper Murrees, but GILL distinguishes the finer grained sandstones with a characteristic spheroidal weathering from the Upper Murree sandstones. A further distinction is that the latter contain heavy mineral residues rich in epidote and poor in tourmaline, while the contrary is observed in the Kamlial sandstones. Considering the local facies changes it seems evident that a clear-cut separation of the basal Siwaliks from the Upper Murrees is not everywhere possible.

The overlying *Chinji* rocks are well defined by their predominant bright red shales and silts alternating with thin, poorly cemented ash-grey sandstones.

The Lower Siwaliks of the eastern part of the Punjab Sub-Himalayas contain 600-700 m of thick well-bedded to massive green-grey sandstones with mottled, streaky to banded grey and brown weathering colours. Intraformational conglomerates are also reported. These Nahan sandstones of GILL (1951) are overlain by bright red clays with thinner sandstone intercalations, some containing stringers and pockets of pebbles (quartzites and gneisses) in distinction to the underlying Nahan sandstones. It is questionable whether the Nahan sandstones with their overlying brightly coloured shales could be correlated with Kamlial and Chinji of the Potwar region. Even the boundary between Lower and Middle Siwaliks within the alternating red shales and sandstones is here difficult to trace. The approximate thickness of the Lower Siwaliks in the Potwar basin is 2000 m.

Middle Siwaliks

The Middle Siwaliks lie in an intermediate position between the Lower Siwaliks, still bearing considerable affinities to the Murrees with their Peninsular shield influence, and the conglomeratic Upper Siwaliks reflecting the major Himalayan orogeny. In the Potwar area they are divided into a lower Nagri and an upper Dhok Pathan section. Again, this subdivision is scarcely recognizable in the more eastern Siwalik profiles.

The Nagri formation is predominantly sandy, with a clear-cut contact towards the underlying Chinji. The thick-bedded to massive sandstones contain thin, reddish, shaly intercalations. They grade, partly through lateral facies changes, into most conspicuous horizons of yellow to orange and variegated clays and silts with thin intercalations of whitish and brown sandstones, which make up the bulk of the *Dhok Pathan.* In the eastern Punjab foothills the Nagri-type sandstones are well developed as micaceous, salt-and-pepper coloured, irregularly cemented sandstones with large concretionary lenses containing frequent fossil bones and teeth. In the corresponding Dhok Pathan section pebbly horizons are more frequent and increase towards the Upper Siwaliks. The lower limit of the Upper Siwaliks is still disputed. Faunal and lithological breaks do not coincide and, according to WADIA (1928) and confirmed by GILL (1951), the base of the Upper Siwaliks should be placed below the widespread Siwalik conglomerate, within the brown sandstones of the Upper Dhok Pathan. This level is characterized by an Upper Siwalik fauna, but where faunal control is missing a well-defined stratigraphical limit between Middle and Upper Siwaliks cannot be established because of the facies changes and particularly the heterochronous conglomerate levels. Except for local conglomerate fans in the western Potwar basin, which clearly originated from an ancient western Indus River active between the Upper Nagri and the Dhok Pathan times (Fig. 14), all major conglomerate levels should be included in the Upper Siwaliks or younger formations. This is particularly true for the conglomerate levels in the Siwaliks of the more eastern foothills.

The early Indus conglomerates of the Dhok Pathan contain fragments of gneiss, quartzites and sedimentary rocks from Palaeozoic to Eocene age. Eastwards they die out, for their source lay along the Indus River in the west. A peculiar change was observed by GILL at the tail of such a conglomerate layer; after thinning to about 10 m, it suddenly changed into a sub-angular boulder bed with fragments of Murree and Kamlial sandstones up to half a metre in diameter, and with only scattered remnants of older rocks. Evidently the enclosed sandstones must have been consolidated prior to their erosion. Similar tail ends of conglomerates were observed in nearby levels. All conglomerates found in the Middle Siwaliks are conformable. The sudden appearance of large Tertiary boulders may, however, indicate that towards the end of the Middle Siwaliks some Himalayan orogenic movements may already have involved some sediments of the Potwar basin (GILL, 1951).

The average thickness of the Middle Siwaliks of the Potwar region is, according to GILL, 1000-1500 m.

Upper Siwaliks

The Upper Siwaliks reflect a profound change in the environment of sedimentation after the depo-

sition of the early Siwalik sediments, with their remarkably constant regional development suggesting a strong influence of longitudinal river transport and partial admixture of material from southern sources. Coarse, fan-shaped, deltaic deposits reflect the onset of the rather sudden and strong orogeny of the southern Himalayas. We can visualize the resulting flooding of a landscape populated by many species of elephants. The Upper and post-Siwaliks, with their counterparts in the Karewa beds of the Kashmir Valley, give us ample evidence of the youngest and most active history of the Himalayan chain.

The Upper Siwaliks begin in the *Potwar basin* with brown sandstones and deep-red clays and silts. It is within these brown sandstones that, according to WADIA's faunal evidence, the base of the Upper Siwaliks must be placed. The brown sandstones are correlated with the lowest subdivision of the Upper Siwaliks—the *Tatrot stage*. Above follows the *Pinjor stage*, here conglomeratic, with intercalations of deep-red to pinkish clays and silts and brown gritty sandstones. The conglomerates are generally lenticular and subject to rapid facies changes. Contrary to some earlier investigators (DE TERRA, 1936, 1939) GILL stresses the *conformable* aspect of the Siwalik conglomerates. This is in line with the earlier observations of PILGRIM in 1910. *No major unconformity is known within the Siwaliks* of the Potwar basin, and, as we will see, no such unconformity is apparent in other Siwalik sections. The main Himalayan diastrophism has affected the Siwaliks as a whole, and the clastic rock sequence demonstrates only smaller and local disturbances.

In the *eastern Punjab* foothills the conglomeratic stage of the Upper Siwaliks is well developed. Here the base of the Upper Siwaliks seems to coincide with the base of the conglomerates, which cover the underlying sandstones and silts with a conformable contact. From north of Bilaspur, near the Sutlej River, GILL (1951) describes conglomerates with pebbles and cobbles of slates, quartzites and granitic gneisses changing suddenly into a rock made up of purple Murree-type sandstones and Eocene limestones. This facies change within a conglomerate horizon is reminiscent of the tail ends of the already mentioned conglomerates of the Potwar basin. The conglomerates generally contain intercalations of grits, sands, and red and brown dirty sandy to silty clays. In the upper part of the section, the clays are indistinguishable from the alluvial clays of the Punjab plains. Coarse conglomeratic horizons of the Upper Siwaliks were called boulder conglomerates, and this term has been used as a *stage* (really formational) name and placed above the Pinjor *stage*. Since conglomeratic levels, even of the boulder type, can occur in lower sections of the Siwaliks, the general term *Siwalik conglomerates*, or *Upper Siwalik conglomerate*, where it is defined as such, is prefered.

In the Potwar basin the Upper Siwaliks measure 1500-2000 m. Since the top is an erosion surface the original thickness of the Upper Siwaliks could have been considerably more. In the eastern Punjab foothills the conglomerates are thinner, but at least 500 m are exposed.

The age given to the Siwaliks depends so far entirely on their prolific vertebrate faunas (mainly mammalian) and the correlation of these faunas with dated sections elsewhere. Palynological research has only begun, and its results have not yet advanced far enough to add significantly to the Siwalik stratigraphy. Following WADIA (1951), the Siwaliks span a time period from the Middle Miocene to the lower Pleistocene, with the Lower Siwaliks as Middle to Upper Miocene, the Middle Siwaliks as Upper Miocene to Middle Pliocene, and the Upper Siwaliks as Upper Pliocene to Lower Pleistocene (Fig. 13). Considerable uplift in the Himalayan hinterland is reflected by the deposition of Upper Siwalik conglomerates of early Pleistocene age. The main orogeny, embracing the Siwalik sediments as a whole, took place towards the end of the Lower Pleistocene, with a marked unconformable overlap of post-Siwalik sediments. This post-Siwalik orogeny was most intense along the Himalayan foothills and diminished gradually towards the foreland.

Structures of the Siwaliks

In the Potwar basin as well as along the Siwalik belt of the eastern Punjab Himalayas GILL (1951) distinguishes from south to north three major zones of deformation:

1. A zone of open folding.
2. A fault zone with steeply northwards-dipping reversed faults of great lateral extent, with intervening open folds (western area) or gently dipping monoclines (eastern area).
3. A zone with closely spaced strike faults and severely compressed folds, bordered by the so-called Main Boundary Fault, delimiting the Sub-Himalayas from the Lower Himalayas.

In both the gently folded and the more strongly affected areas of the Siwaliks in the Punjab Himalayas the dominant broad synclines or gently inclined monoclines contrast with the narrow sharp and steep anticlines to give a quite characteristic feature. The structures are well reflected in the elongated depressions (the characteristic Duns) of the Siwalik belt. Most of the strike faults are steep at the surface, and some evidence from bore holes in the Potwar region indicates steep faults also in depth, though I doubt that these depths are sufficient to rule out the possibility of a gradual or even sharp turning over of the steep faults into less inclined or

flattish levels of detachment in an incompetent horizon. The vertical upthrusting envisaged by GILL, with no relation to the tangential stresses associated with the folding is somewhat difficult to understand (LEES, 1949) (Fig. 15).

One of the most marked structural features bordering the Siwaliks of the eastern Punjab foothills is the *Jammu strike fault* (WADIA, 1928), which can be followed over 250 km. Northeast of this fault occur the inliers of Permian and Eocene marine rocks to be discussed in the next section (p. 85). The northeasterly dip of the fault changes from 30° to over 70°, and there is a possibility that at depth it turns into a thrust fault with a more gentle dip. The changes in surface dip may in fact represent different erosion levels of a curved plane, but this remains to be proven. Upthrusting is also suggested by GILL for the Jammu strike fault. His argument that it is not a folded thrust, comparable to AUDEN's Krol thrust, since the fault trace is rectilinear and windows or klippen are absent, is not convincing, particularly if one assumes a considerable steepening of the thrust fault towards the surface outcrop with the horizontal component at greater depth. This picture is frequently observed in foothill structures (Rocky Mountains) where geophysical and drilling control is complete. Tangential stresses of the Himalayas, probably related to a relative northwards movement of the shield spur towards the western Himalayan syntaxis, may after all be the major cause of the strike faults, which actually resemble steep thrusts (Fig. 15).

Post-Siwaliks and the Karewa Beds of Kashmir

The Siwalik orogeny closed the conformable Siwalik sedimentation, and with it came the surprisingly sudden extinction of most of the highly prolific Siwalik mammal faunas. Younger deposits follow with a marked unconformity. In the Potwar basin the younger transgressive conglomerate horizons have often been mistaken for Upper Siwalik conglomerates, with the implication of a strong Upper Siwalik unconformity (DE TERRA and DE CHARDIN, 1936). It is the merit of GILL's careful investigation that at least for the Potwar basin this unconformity is shown to be of post-Siwalik age, and thus falls *within* the Pleistocene rather than at the base of the Pleistocene (the *Lei* conglomerate of GILL, 1951).

A still unsettled and important question is whether the uppermost Siwaliks are related to the *earliest glacial stage in the Himalayas.* Direct relations of Upper Siwalik deposits to known glacial stages are missing. To the author's knowledge the only occurence of glacial deposits within the Upper Siwaliks was observed in the eastern end of the trans-Indus continuation of the Salt Range. The careful investigations by MORRIS (1938) leave little doubt that his *Bain boulder bed*, 2000 m below the top of the locally strongly folded, Siwaliks, resembles a tillitic deposit. The faunas above and below the boulder beds show affinities to the European Villafranchian (Lower Pleistocene) and the glacial episode is correlated with the Alpine Günz.

In the *Bain boulder bed* a wild mixture of unsorted boulders and pebbles is embedded in an unsorted greywacke-like matrix. Sedimentary rock fragments dominate, but crystalline boulders do occur. The occurence of true striated and polished fragments is rather doubtful (see also discussion of COULSON, 1938). Lithologically the Bain boulder beds show some similarity with the Gondwana Talchir boulder beds, and contrast with the surrounding normal Siwalik conglom-

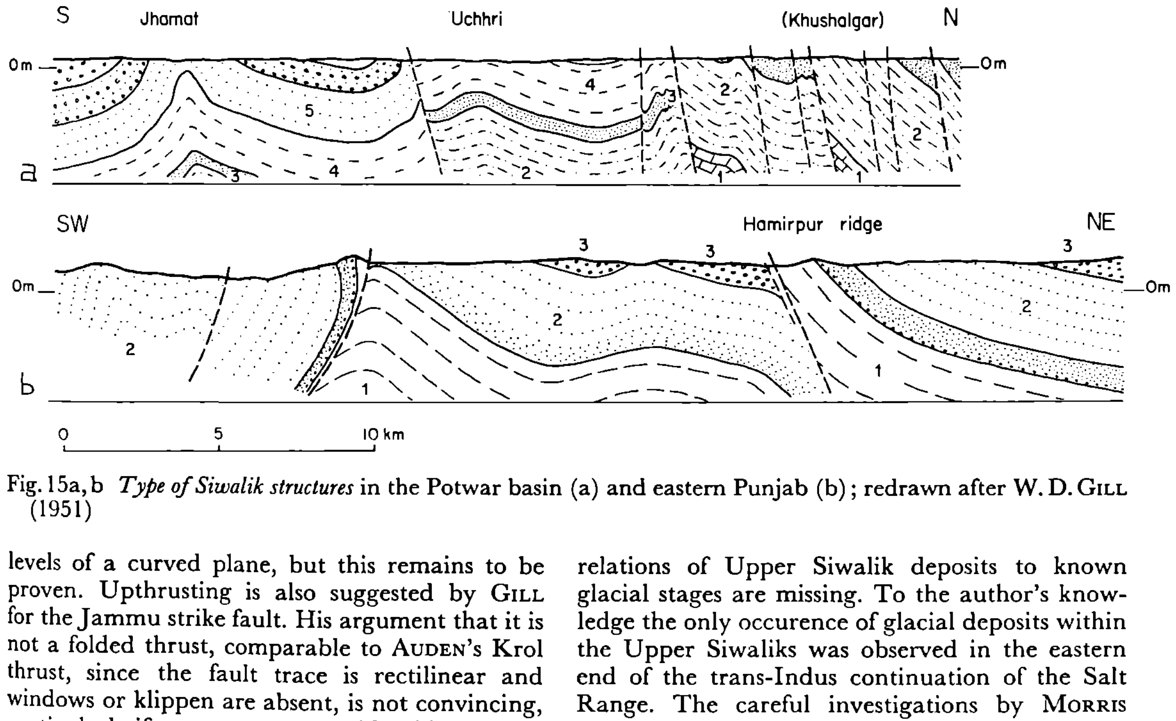


Fig. 15a, b *Type of Siwalik structures* in the Potwar basin (a) and eastern Punjab (b); redrawn after W. D. GILL (1951)

erates. Their source is believed to be the Afghan hinterland to the west. Though the lithological aspect of the Bain boulder bed is certainly similar to that of glacial formations, the author wonders if no alternative explanation could be possible. With a Himalayan hinterland glacial influences should be more frequently felt than just this one boulder bed in the extreme western area, where the hinterland is of less pronounced elevation, and must have been particularly so prior to the main Siwalik orogeny. It seems more likely that even during the Lower Pleistocene desert conditions were increasing in a westwards direction, with a corresponding reduction of the early glaciation. Could not the formation of fanglomerates, caused by sudden cloudbursts, and so typical in deserts, produce similar effects to those of a glaciation? The author has seen many desert fanglomerates which, except for the absence of clearly striated boulders, could hardly be distinguished from glacial boulder beds, and certain mud flows can have striated pebbles unrelated to glaciation. Are the reported striated pebbles of the Bain boulder bed really glacial pebbles? The question of the origin of the Bain boulder bed is a most important one, since the acceptance of its glacial origin would indicate *an early glaciation prior to the Siwalik orogeny*, which means prior to the main Himalayan diastrophism, a fact unique in such circumstances and certainly difficult to understand.

In the *Potwar basin*, unconformable, post-Siwalik conglomerates have been called *Lei conglomerates* by Gill. These cover extensive areas of the northern Potwar. They are poorly graded and their composition varies, consisting predominantly of Eocene limestones with a small proportion of older sediments, quartzites and igneous rocks. Sands and silts of a pale brown to ochre colour are intercalated; the silts are reportedly of aeolian origin. The thickness of the Lei conglomerates does not exceed 100 m. After the deposition of the Lei conglomerates, with their sands and silts, the succeeding period of gentle denudation coincided with an *early Palaeolithic culture* (Soan culture—probably Middle Pleistocene). The period of man's habitation seems to have been suddenly arrested by the onset of thick silty loess deposits, possibly coinciding with a marked glaciation in the Himalayas. Only Neolithic remains are known from the younger beds in the Potwar region. Renewed and probably rather sudden melting of glaciers produced a widespread veneer of gravels containing some large boulders reported to have unmistakable glacial facets. According to Gill they may have been transported in blocks of ice by flood waters. I believe, rather, that they are relics of fanglomeratic outwash floods, which could carry large boulders without ablation over considerable distances.

In the *eastern Punjab foothills* a thicker section of the Upper Siwalik conglomerates seems to have been preserved than in the Potwar region, and the gap to the transgressive post-Siwalik deposits is less wide. In the southern foothills the latter are rarely preserved, but corresponding horizons are found in the upper part of the famous *Karewa lake beds* of the Kashmir basin. In spite of the occurence of the Karewas within the Lower Himalayas of the Punjab, and not in the Sub-Himalayas, we prefer to discuss them together with the Upper Siwaliks and post-Siwaliks, since they bear the major evidence regarding the glacial influence and its relation to the main diastrophism.

Karewas

The Karewas of Kashmir are separated from the Siwaliks of the eastern Punjab by the Pir Panjal Range, which borders the Kashmir basin on its south side. Godwin Austen, 100 years ago (1864) recognized the great significance of the Kashmir lacustrine deposits for the younger geological history of the Himalayas. Dainelli, in his monumental work on the glacial period of NW India (1922) suggested a *Pleistocene uplift* of 2000 m for the Pir Panjal Range, based on the uplifted and tilted Karewa lake deposits. Since the excellent monograph of De Terra (1939), where the greater part is devoted to the youngest formations of the Kashmir Valley, our knowledge of the important Karewa beds has been greatly improved.

The Karewas are divided by a marked unconformity into the Lower and the Upper Karewas. The glacial influence is very pronounced in the Upper Karewas, but still rather uncertain in the Lower section. *The Lower Karewas* (Fig. 16) are generally underlain by local gravel fans with intercalations of pink to brown sandstones and sands. These fans are related to uplift and erosion of the Pir Panjal in the south and the Himalayan range in the north, although the amount of uplifting seems minor. The fans transgress the underlying Mesozoic, Palaeozoic or Trap rocks, sometimes with a locally developed basal breccia or conglomerate. Sandstones and gravels of the fans often show cross bedding and marked lateral facies changes, mainly from coarse to fine material. They seem related to a major drainage system, and between the ancient river courses they can be missing. The maximum thickness observed for these fan gravels amounts to 300 m. Some authors correlate them with the first glacial stage in the Himalayas and the Pir Panjal, but evidence from the Pir Panjal shows that only minor and surprisingly thin clay moraines are present in the higher mountainous regions. It seems to me still questionable if these small and apparently rather

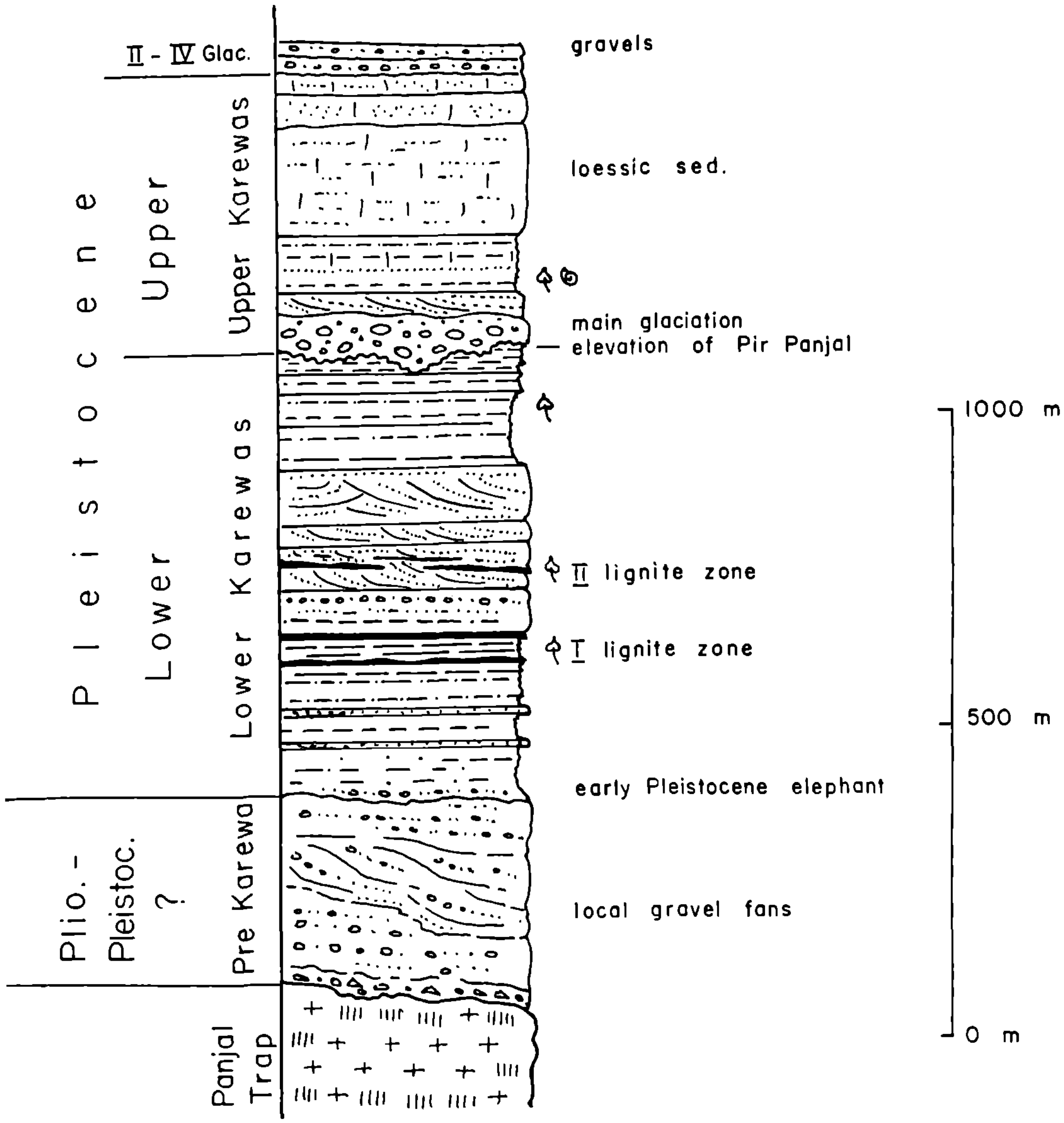


Fig. 16 *Stratigraphy of the Karewa beds.* Kashmir. Punjab Himalayas; compiled mostly after De Terra and De Chardin (1936), Wadia (1951)

insignificant remains can be taken as representatives of the first glaciation and correlated with the much better developed glaciation of the northern Himalayan range. The basal gravel fans, underlying the lacustrine Karewas, are certainly not the outwash of those problematic thin clay moraine remnants and therefore hardly related to a first glaciation.

Above the gravels, as well as interfingering laterally, follow well-bedded, locally varved clays and silts with thin sandstone horizons. Locally basal bone beds are present, in which remnants of an early Pleistocene elephant were found. Typical are lignite intercalations covered by sands and conglomerates (Fig. 16). A second, higher lignite zone follows within brown cross-bedded sandstones overlain by a thick section of laminated bluish grey clays with silt and thin sandstone intercalations, containing some well-preserved plant remains.

Part of the upper Lower Karewas was eroded after having been folded and uplifted, and was subsequently transgressed by the *Upper Karewas*. According to De Terra (1939) a maximum of 800 m of Lower Karewas has been preserved, and probably a similar amount was eroded.

The Upper Karewas transgress the clays of the Lower Karewas, their coarse gravels grading upwards into greenish sands consisting predominantly of Panjal trap material on the southern side of the basin. The gravels have been related by Wadia (1951) to the second glaciation. Clays

			FLUVIAL DEPOSITS OF THE PUNJAB-HAZARA SUB-HIMALAYAS			GLACIAL DEPOSITS IN PIR-PANJAL RANGE—ICE AGE IN KASHMIR			
			Stages		*Fossils*		*Stages*		*Fossils*
HOLOCENE			Recent alluvium, scree, etc.		Living species.		Recent alluvium of the Jhelum.		Modern plant and animal species.
PLEISTOCENE	UP		Newer terraces and gravel caps.	2,500 feet	Proto-Neolithic tools of Man.		Moraines and terraces of *IV. GLACIAL STAGE.* *III. GLACIAL STAGE.*		
			Loess deposits.		Camel, horse, bison, wolf.	KAREWA SERIES UP	Well-bedded sands and clays with boulders and erratics, varve clays. Basal boulder-bed. *II. GLACIAL.*	1,000 to 1,500 feet	Plant fossils locally abundant; many gastropod and other land molluscs.
	MID		Older gravels and terraces.		Acheulian tools plentiful.				
	LR	UPPER-SIWALIK	Boulder-conglomerate (Villafranchian) stage.	6,000 to 8,000 feet	*Elephas namadicus, Bos, Equus, Camelus, Buffelus.*	KAREWA SERIES LR	Fine buff and blue-grey shales, sands, and gravels, cross-bedded, varve clays. *I. GLACIAL.*	4,700 to 5,000 feet	Fossil leaves, fruit and spores of rose, cinnamon, oak, maple, walnut, trapa; diatoms, land-shells.
PLIOCENE	UP		Pinjor stage (Astian).		*Elephas planifrons, Elephas hysudricus, Stegodon, Bos, Boselaphus, Hemibos.*		Dark, often carbonaceous, shales and sandstones with thick conglomerate beds and lignite seams. *PREGLACIAL.*		*Elephas hysudricus, Rhinoceros* sp., *Cervus* sp., Schizothoracine fish; bird and ungulate bones, teeth, etc. Sub-tropical lowland plants.
			Tatrot stage (Plaisancian).		*Leptobos, Hippohyus, Sivatherium, Rhinoceros, Giraffa, Mastodon sivalensis.*		Pre-Tertiary.		
	MID	MID-SIWALIK	Dhok Pathan stage (Pontian).	4,500 feet	*Mastodon, Hippopotamus, Merycopotamus,* large giraffoids, *Teleoceras, Listriodon.*				
	LR		Nagri stage.		*Dinotherium, Prostegodon, Hipparion, Dryopithecus* and other anthropoids.				

Fig. 17 *Correlation chart of the Plio-Pleistocene of the Punjab Sub-Himalayas and the Karewa basin of Kashmir; reproduced from* D. N. Wadia (1951)

(partly varval), silts and yellowish sands continue the section. They contain plant remains and molluscs, and are topped by a thick layer of light-yellow silts and ochre sands, the silts probably representing partly redeposited loess. These sediments, to some extent of lacustrine and aeolian origin, are followed by loams, in which a complex system of gravel terraces reflect the younger glacial stages (third and fourth stages).

The correlation of the Karewas with the Siwaliks and post-Siwaliks

WADIA gives a correlation chart of the Upper Siwaliks and the Karewa beds based on DE TERRA and other workers (Fig. 17). He correlates the Lower Karewas with the Upper Siwaliks and places the first glacial stage within the Lower Karewas. This glacial influence could thus be compared with the presumed glacial remains within the Upper Siwalik conglomerates (Bain boulder beds), but as we have already mentioned the evidence for glacial influence in the Siwaliks is not very convincing. The glacial influence within the Lower Karewas or even at the base of the Karewas is equally weak (DE TERRA). Varved clays do not necessarily reflect glacial conditions at all, and the meagre remnants of the first glaciation in the Pir Panjal, where the greater part of the Lower Karewas is preserved, seems very doubtful evidence. We have seen that a major paroxysm and a main glaciation, actually the strongest Himalayan glaciation, fall between the Lower and the Upper Karewas. This paroxysm can be correlated with the deposition of the Lower Karewas. The uplift was probably responsible for the strong glacial stage in the Pir Panjal Range, which, prior to this uplift, hardly reached the necessary level for an earlier glaciation. The post-Lower Karewa paroxysm can be well correlated with the post-Siwalik orogeny, as indicated on the Table by WADIA (Fig. 17).

The main glaciation, or the second glacial stage of some authors, is followed by a clear interglacial period. Subsequent to this interglacial, two more glacial stages are generally reported. It is doubtful, however, whether the two last Himalayan glacial stages were interrupted by an interglacial or only by an interstadial period. The latter seems more likely, and more in line with the younger uplift of the Himalayan range, if we compare the history with the Alps and the Alpine glacial stages.

Kargil Basin

120 km northeast of the Kashmir basin, just south of the Indus River and still within the northeast part of the Punjab Himalayas, lies the small *Kargil basin*, famous for its well-developed Pleistocene terraces and their relation to the glacial history of the high Himalaya region (Fig. 18). As a more northerly and higher, though much smaller replica of the Kashmir basin, we may include it in our present discussion of the Pleistocene.

Younger Tertiary deposits of Siwalik type are not present in the Kargil basin, though some of the lower gravel fills may be equivalent to

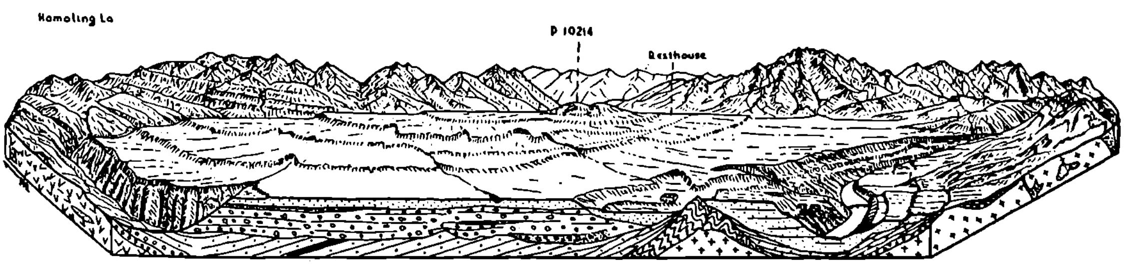


Fig. 18 *Block-diagrammatic sketch of the Kargil Basin,* NW Himalayas; reproduced after H. DE TERRA (1935)

the Siwalik orogeny, which was active *after* the deposition of the Upper Siwalik conglomerates. Thus the Upper Karewas would correspond to the post-Siwalik sediments (WADIA, 1951).

Most authors agree that the Karewas are predominantly lacustrine sediments, with a strong glacial influence in the upper beds. Folding and uplift affected them during their deposition, especially *after* the intra-Karewa paroxysm. The remarkable uplift of more than 2000 m in an astonishingly short time happened only after some of the Upper Siwalik and Pleistocene conglomerates in the southern foothills, but the distances are too great for exact correlation.

DAINELLI's extensive studies in the northwestern Himalayas (1922) include the Kargil basin, where he distinguishes four main glacial stages. DE TERRA (1935) comes to a similar conclusion. Like the Kashmir basin, evidence here for a first though weak glaciation is inconclusive. A very marked second glaciation could be correlated with the post-Lower Karewa stage,

coinciding with a strong uplift and consequent erosion. This main glaciation seems to be followed by an interglacial period, with lake and gravel deposits devoid of glacial influence. The succeeding third and fourth glacial cycles were rather small, and the intervening stages were certainly not interglacial but *interstadial.* Related to the main glaciation, as well as to the later glacial cycles, are very marked terrace levels in the Kargil basin. These terraces are sharply outlined, and intermediate stages or transitional features are rare.

Such sharp terracing is still a great puzzle, and can hardly be explained without the assumption of rather *catastrophic events* as their cause. In most high mountain ranges much more catastrophic events than is generally believed occured during Pleistocene to Recent glacial phases. *The outbreak of glacial lakes,* formed by the terminal moraines of retreating glaciers, may be one of the very widespread causes. The author has seen evidence in many mountain ranges, and historical outbreaks are well recorded from such areas as the Andes of Peru. In the Himalayas as well as the Karakorum evidence for Pleistocene and Recent lake outbreaks is accumulating. The writer has seen hardly an end moraine which has not been breached by the sudden outbreak of an overspilling glacial lake. The fanglomeratic material intimately mixed with moraine, is transported down the valley and forms gravel fans in the lower reaches. A diagnosis regarding the origin of these fans is extremely difficult. In addition to glacial lake outbreaks from terminal moraines, the Karakorum shows excellent examples of valley damming by lateral glaciers. In late Pleistocene and early post-Pleistocene large lakes were thus formed, recognizable by the remnants of lacustrine deposits (Askot region, DAINELLI, 1922). The sudden break through of such lakes has the same effects as the collapse of a terminal moraine dam. The resulting fanglomeratic masses, often mistaken for moraines and direct evidence of glaciation, can be quite misleading in the interpretation of the glacial history. Even in the well known Alps some interpretations of glacial events are still disputable. A surprising development of Pleistocene terraces is found in the upper, Tibetan part, of the Sutlej River and will be discussed when dealing with the Kumaon Himalayas and southern Tibet.

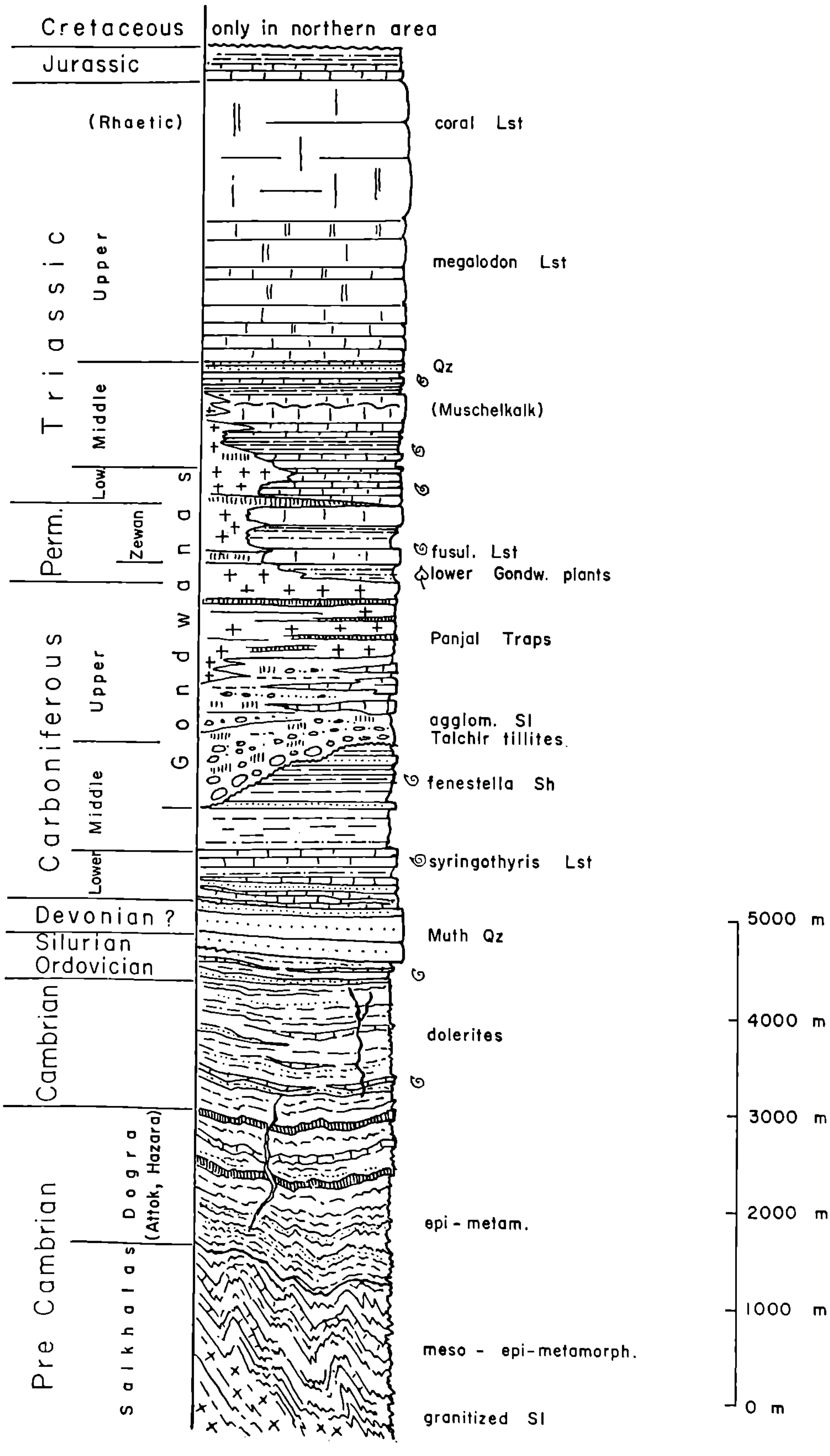
LOWER HIMALAYAS OF THE PUNJAB

In contrast to the Himalayan range further east, the fossiliferous formations of the northern Himalayas (Tibetan Himalayas) transgress the crystalline of the main range and are well developed in the Kashmir region. Westwards they continue around and over the Himalayan syntaxis into the Hazara ranges north of the Potwar basin. The classical division into Lower Himalayas, "barrier forming" Higher Himalayas, and a northern sedimentary and fossiliferous Tibetan Himalayas, is less pronounced in the western Punjab Himalayas, but is well outlined in their eastern part. The western Himalayan syntaxis is responsible for these aberrant tectonic trends and their influence on the sedimentary history of this region.

For easier reference, and in order to avoid lengthy descriptions, the author has compiled stratigraphical columns. Those for the Punjab have been based on various sources, with the bulk of the information coming from WADIA's publications (1928, 1931, 1953 and others) (Fig. 19).

In the Lower Himalayas of the western Punjab the sedimentary record is based on good faunas, and the stratigraphical sections can be followed from the Precambrian into the Jurassic, while younger deposits are more restricted to the northern areas. Where proven Cambrian is preserved, the Precambrian age of the underlying semi- to fully-metamorphosed formations is evident, but such conditions are rare. Except for the region under discussion no proper age assignment is possible for the larger part of the metamorphic formations, particularly in the usually unfossiliferous Lower Himalayas. Earlier investigators classified most of such metamorphics as "old" Central Gneisses, based partly on the idea that the central high range was predominantly built by metamorphic and igneous rocks. ODELL (1943) has stressed the fact that most of the highest peaks are built of sediments, often with a surprisingly low metamorphic grade, and that only the bases are formed by higher grade crystallines. This important fact, well known to all recent investigators of the Himalayas, leaves one most important question still unanswered, i.e. *the stratigraphic age of the metamorphics and the age of the metamorphism.* I see here the most important problem in Himalayan geology, and only very careful detailed studies, petrological as well as structural, coupled with age determinations of carefully selected samples will eventually lead to some better understanding. Experience from Alpine rocks has clearly shown how important the selection and the age dating by three methods on the same sample and on various minerals can be, and how misleading results can be obtained if only one set of relations, e.g. the potassium-argon of the biotite, are considered alone (see later).

Fig. 19 *Stratigraphy of the Punjab Lower Himalayas* (excl. Spiti); compiled from D. N. WADIA and other sources


Cretaceous
only in northern area
Jurassic
(Rhaetic)
coral Lst
Triassic
Upper
megalodon Lst
Qz
Middle
(Muschelkalk)
Low
Perm.
Zewan
Gondwanas
fusul. Lst
lower Gondw. plants
Carboniferous
Upper
Panjal Traps
agglom. Sl
Talchir tillites
Middle
fenestella Sh
Lower
syringothyris Lst
Devonian ?
Muth Qz
Silurian
Ordovician
Cambrian
dolerites
Pre Cambrian
Dogra
(Attok, Hazara)
epi - metam.
Salkhalas
meso - epi-metamorph.
granitized Sl
5000 m
4000 m
3000 m
2000 m
1000 m
0 m

Precambrian rocks

The oldest rock sequence in the Lower Himalayas of the western Punjab region is the *Salkhalas*, corresponding to the Jutogh of Simla or more generally the Vaikritas (Sanskrit for metamorphosed) of the Central Himalayas. They are furthermore correlated with the Dharwars of the Peninsular shield.

Salkhala Schists

The Salkhalas (a name introduced by WADIA) consist of schistose to phyllitic thin quartzites, calc schists, carbonaceous slates, sericite schists and white marble intercalations. They outcrop with a rather low-grade metamorphism in the Shams Abari synclinorium of the western Kashmir, where they form the base of a well-exposed Palaeozoic section. Striking NNW and then NNE into the Nanga Parbat area they gradually become granitized (see later). They turn around the western syntaxis, being thrust centripetally over the Palaeozoic and Mesozoic (Fig. 20). In the Kashmir region the Salkhala outcrops are often characterized by an intense fine zig-zag crumpling of the schistose rocks. The characteristic marbles, often showing white and partly dark-grey, are lithologically not unlike some of the young Palaeozoic Karakorum and Hindu-Kush marbles, from which they must be distinguished by their definitely old Precambrian age. This shows that even in the Karakorum ranges some marbles, if not dated, could also belong to some older horizons.

2000-3000 m of Salkhalas outcrop in Kashmir. Their highly metamorphosed and granitized equivalents in the Nanga Parbat are considerably thicker. Since they are overlain by the Precambrian to early Cambrian Dogra slates their age must be definitely Precambrian.

Dogra Slates

Above the Salkhalas and without apparent sharp break come the Dogra slates, a strikingly uniform formation of predominantly argillaceous deposits such as black and greenish slates and grey and green chloritic phyllites. Lenticular quartz veins occur locally, while arenaceous deposits are practically absent except for some fine quartzitic partings in the slates. Interbedded in the slates one observes some amygdaloidal altered lava flows, mostly changed into chloritic schists. The slates expose a remarkable oblique cleavage which can turn into a fine foliation.

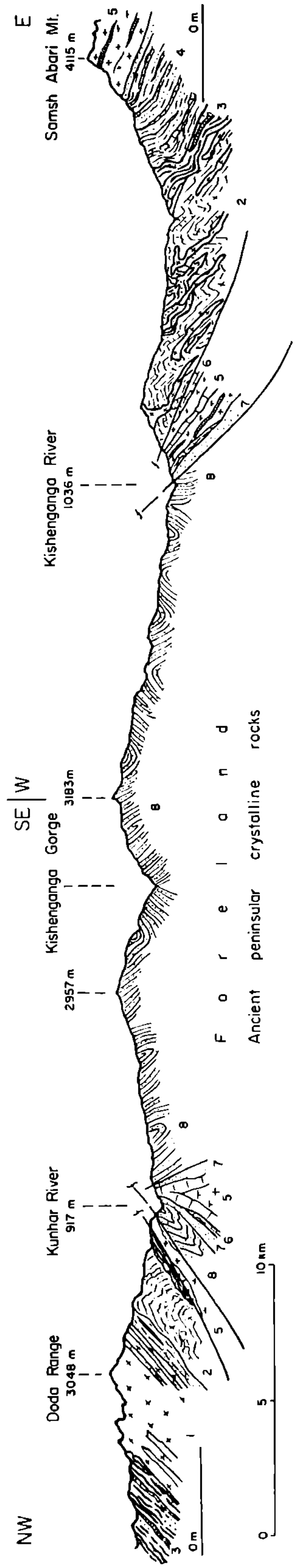


Fig. 20 *Section across the western Himalayan Syntaxis;* redrawn after D. N. WADIA (1931)

1	granitic gneisses	5	Panjal Traps
2	Salkhalas with intrusions	6	Triassic
3	Dogra slates	7	Eocene
4	Cambro-Silurian	8	Murrees

On the west side of the Himalayan syntaxis the *Attok slates*, and further north the *Hazara slates*, form identical deposits, and correspond to the *Simla slates* in the western Kumaon Himalayas. The bottom and top of the Dogra slates are not well defined. They are often in thrust contact with the underlying Salkhalas, or, if altered by a higher grade metamorphism (northern areas) they are indistinguishable from the latter. Upwards they grade into more arenaceous beds and greywackes with few lenticular limestones. The sandy layers are rich in animal burrows and may be part of the Cambrian. The top of the Dogra slates could be placed below the first well-marked sandy layers, which leaves them with a thickness of about 2500 m.

The argillaceous Dogras are generally compared with the Vindhyans of the Peninsular shield. The latter, as uniformly arenaceous sediments, seem to change gradually towards the Himalayas into more argillaceous beds. Evaporitic sediments seem to indicate a change from continental towards marine conditions, well represented by the intermediate Saline Series of the Salt Range. We have already seen that part of the Vindhyans may reach into the Cambrian, and the transitional border between Dogras and proven Cambrian suggests for the Dogra slates a late Precambrian to earliest Cambrian age. The regional unconformity dividing the Indian shield deposits into older Dharwars and younger Puranas disappears towards the northwards-deepening basin which borders the shield to the north and contains the sediments involved in the Himalayan orogeny.

The very thick argillaceous deposits representing the oldest Himalayan sedimentary rocks are very widespread all along the Lower Himalayas and, as we will see, form the base of the main sedimentary sequence of the higher ranges and thus of the Tibetan sedimentary zone. Dogras and Salkhalas may after all represent deeper geosynclinal sediments of the Precambrian which change gradually into shallower deposits with the beginning of the Palaeozoic.

Palaeozoic sequence from the Cambrian to the Lower Carboniferous

Developing from the argillaceous Dogras, the Cambrian begins with greywackes, shales and thin lenticular limestones. They imperceptibly grade into massive bluish slates and oolitic limestones, in which crowds of tribolites and brachiopods of Middle to Upper Cambrian affinities occur locally. Strangely enough, this fauna is strictly provincial, with no relation to the faunas of the Salt Range, the Spiti area, or the Persian Gulf. On the other hand, affinities exist with the Cambrian of Indo-China (WADIA, 1953). The difference from the Spiti Cambrian is particularly surprising since the Kashmir-Spiti basins must have been connected over the now existing Himalayan divide. A faunal similarity certainly existed in the post-Cambrian deposits.

The strata overlying the thick arenaceous and argillaceous Cambrian, which can vary from 1000 to 2000 m, include sandy shales and impure limestones with an Ordovician and Silurian fauna, the whole sequence being only about 50 m thick. No sharp break with the underlying Cambrian can be noted, and apart from a slight increase of the calcareous beds the lithology has changed little.

At this level a striking change in the lithology takes place, not only in Kashmir, but over nearly the whole Himalayas. With a sharp, but still conformable contact, the rather monotonous argillaceous series of the Lower Palaeozoic are overlain by ridge-forming snow-white quartzites, called the *Muth quartzites* from Muth in the Spiti region. The 500 m thick massive quartzite beds are devoid of fossils, and are conformably overlain, again with a sharp contact, by fossiliferous Lower Carboniferous limestones. The Muth quartzites, occuring between Silurian and Lower Carboniferous, have been generally accepted as *Devonian.* This does not, however, preclude the possibility that the quartzites still belong to the Silurian, and that a gap exists between the Silurian and the overlying Carboniferous. Such a gap, although of a much wider range, has been recently discovered in the Elburz Range, the Iranian continuation of the Pamirs (or at least a branch of it), where Middle Cambrian is conformably followed by Upper Devonian in a marine calcareous facies, and where the so far "classical Old Red" of supposedly Devonian age has turned out to be pre-Middle Cambrian (STÖCKLIN, RUTTNER and NAVABI, 1964).

In the northwestern part of Kashmir, locally preserved below the Upper Carboniferous Gondwana transgression, and following conformably over the Muth quartzites, we observe up to 1000 m of thin-bedded grey limestones with thin intercalations of shales and quartzites. The rich brachiopod faunas of these limestones indicate a *Lower Carboniferous age.* The large amount of limestones distinguishes this horizon which corresponds to the Lipak Series of Spiti, from the Lower Palaeozoic. Over an intermediate series of quartzites that follow above the limestones, we reach the *Fenestella* Shales, black sandy shales rich in *Fenestella.* Intercalations of quartzites are still present. A maximum of 700 m is preserved below the Gondwana transgression, but the original thickness may have been considerably more. Similarly to the Muth quartzites, the *Fenestella* Shale deposits are widespread, and have been recognized, though more on lithological grounds, in the northern Karakorum underlying the northern sedimentary series (Pasu shales).

Upper Carboniferous to Jurassic and the Gondwana influence

The conformable and rather complete Palaeozoic section in the Lower Himalayas of the Punjab is suddenly interrupted by the transgression of the Permo-Carboniferous with an outstandingly different Gondwana rock sequence.

We already know of the *Gondwana transgression* in the Salt Range (Talchir boulder beds), where, because of its intermediate position between the Peninsular shield and the Himalayan orogenic belt, the Gondwana influence is still strongly felt. It is, however, remarkable that Gondwana rocks are widespread even in the NW Himalayas, and can be recognized, though often on very weak evidence, throughout the whole length of the chain (see later).

Sixty years ago a *Glossopteris* flora was found for the first time in the Northwest Himalayas (NOETLING, 1903). Most important was the discovery of these plant beds occuring together with Permian fossiliferous marine beds, allowing a clear age relation of the Gondwana flora with dated marine horizons. Together with this Gondwana influence, the NW Himalayas were the scene of widespread vulcanism, well developed in the Pir Panjal Range, and therefore called the Panjal Volcanics, or *Panjal Traps.* The volcanic activity was not restricted to a certain horizon, but occured in different regions at different levels, greatly complicating the stratigraphy in this part of the Himalayas. Up to the present times, the genetic relationship of the so-called Agglomeratic Slates, at the base of the Volcanics and the basal Gondwana boulder bed with glacial influence, and again their relation to the widespread tillitic Blaini horizon of the more easterly Simla area, is still disputed. Recent palynological investigations of the various boulder beds may eventually allow some more definite conclusions.

Panjal Volcanics and Gondwana sediments are intimately associated, though the Gondwana sediments are more frequent in the upper zones, where *Glossopteris*-bearing strata are interbedded with volcanic rocks. Often the sediments are overlying the volcanics, and then the base may be formed by locally developed boulder beds with a tillitic aspect.

The Panjal Volcanics begin nearly everywhere with the so-called *Agglomeratic Slates*, transgressing onto Carboniferous or older series, and in Hazara, partly onto the Precambrian. In spite of these progressive overlaps *no marked angular unconformity* can be observed at the base of the volcanics. The Agglomeratic Slates are still a lithological puzzle, and have variously been regarded as tillites, ordinary conglomerates or agglomerates. They are probably a mixture of all three, with a predominance of the volcanic part. In a fine greywacke-like dark-grey slaty matrix are embedded angular quartz grains. Larger components consist mostly of quartzites, slates, limestones and more rarely porphyries. The matrix often contains fragments of devitrified glass and feldspar phenocrysts, which underline the pyroclastic aspect of the slate. Grains and larger pebbles, usually angular, are very badly sorted. Facetted pebbles of possible glacial origin have been observed but are not frequent. At a few localities some fossiliferous intercalations have been discovered with affinities to the underlying *Fenestella* Shales. In other places Upper Carboniferous and or Permian productid faunas were found, which seem to indicate various levels in which agglomeratic slates are developed, corresponding to various horizons of volcanic activity. The Agglomeratic Slates can be followed around the western syntaxis, where the northernmost outcrop below the Salkhala thrust is 1000 m thick, into Hazara.

The Panjal Traps follow above the Agglomeratic Slates with a transitional contact. They consist mainly of thick lava flows of an augite-andesite composition, mostly greenish coloured by epidotization. The rocks are compact, and porphyritic textures are rather rare. They are hemi-crystalline, and practically without phenocrysts. Single flows vary in thickness from one metre to about 10 m, but are in general lenticular. Locally marine sediments in the form of fossiliferous limestones of Permian (lower section) or more rarely of Triassic age (in the uppermost part) are intercalated. The traps can reach a thickness of 2500 m. Usually the vulcanism ceased its activity in the Upper Permian, but in some areas flows have been observed as high as Upper Trias.

In the western part of the Lower Punjab Himalayas the Panjal Traps are conformably overlain by beds corresponding to the *Lower Gondwanas* of the Peninsula, and, since marine fossiliferous horizons are intercalated, a precise age for the Peninsular Gondwanas can be thus established.

The Lower Gondwana sediments of the Punjab Himalayas often begin with a thin basal conglomerate related to the Agglomeratic Slates, which has been correlated with the Talchirs of the Peninsula and the Blainis of the more eastern Himalayas. Siliceous and carbonaceous shales with some cherts and sandstones contain a *Gangamopteris* flora in the lower section and *Glossopteris* in the upper part. Towards the top the sandstones become calcareous and grade into the overlying marine *Permian Zewan Limestones*, the equivalent of the widespread *Productus* Limestones of the Salt Range and the *Productus* Shales of Spiti. In most places the Permian Zewan Limestones form the upper limit of the Gondwanas and/or the corresponding Volcanics. The lime-

stones with intercalated black shales are about 300 m thick and lead to the well-developed and highly conspicuous Triassic limestones and dolomites.

The Kashmir Lower Himalayas display a well developed *Trias*, conspicuous in the steep hills bordering the Kashmir Valley on its northern side. It is a typical representative of the Triassic sections so excellently developed on the northern side of the Himalayas, particularly in Spiti and northeastern Kumaon. WADIA (1953) applies a three-fold division to the Himalayan Trias, based on the Germanic facies. This, in my opinion, somewhat forceful division should be replaced by the East Alpine scheme which is much better suited to the Himalayas and is already applied in the monumental work of DIENER on the Triassic faunas (1897).

The base of the Trias follows conformably and even *transitionally* above the Permian Zewan limestones. In Kashmir and in the Spiti region of the Kumaon Himalayas, this Palaeozoic-Mesozoic transition is of particular interest, and warrants modern detailed investigations similar to SCHINDEWOLF's studies in the Salt Range (1955). In Kashmir (near Kolahoi Peak), the Permian limestones and shales (Zewan Series) grade into the lowest Triassic *Otoceras* beds. The *Otoceras* bed consists of a band of nodulous limestones from which many speciments of *Otoceras* were collected. Curiously enough, in the same *Otoceras* bed a few *Productus* of the Upper Permian were discovered. Ten metres higher there follows another fossiliferous horizon characterized by *Ophiceras*, but containing still one species of *Otoceras* (BION, 1914).

The *Anisian and Ladinian* of the Lower Triassic are characterized by a fine alternation of dark grey shales, nodular, concretionary and platy limestones and some sandy limestones. With the *Carnian*, limestones and dolomites—the latter missing in the lower sections—increase considerably, and the Upper Triassic *Norian* of Kashmir is formed by impressive white walls of massive dolomites and limestones practically barren of fossils. In contrast with the classical Spiti Trias, to be discussed in the section on the Tibetan Himalayas, cephalopods are frequent in the lower part of the Trias, but absent from the upper horizons. This fact and a striking change in lithology in the Upper Trias indicate some interruption of the Upper Triassic basin between Kashmir and the Spiti region north of the Himalayan main range. In the Hazara region only the Upper Trias has been observed so far. Some of the thick limestones and dolomites of the Norian of Kashmir may include part of the *Rhaetic Megalodon* limestones, known from the northern Punjab Himalayas though megalodon horizons are also frequent in the Upper Triassic.

Jurassic horizons are scarce in the Punjab Lower Himalayas. Local outcrops occur in the Pir Panjal Range in the form of tectonized dark shales and limestones squeezed into tight Triassic synclines. More Jurassic is probably covered by the widespread Pleistocene Karewas on the north flank of the Pir Panjal.

Jammu limestones

While discussing the Punjab Sub-Himalayas we have already cursorily mentioned the peculiar Palaeozoic ranges rising out of the Murrees of the *Jammu region* over 25 km south of the Main Boundary Fault—the contact line against the Lower Himalayas. The presence of marine limestone formations at a considerable distance south of the actual Himalayan range is rather unexpected, and merits our special interest.

The conspicuous white limestone range, which contrasts strongly with the low reddish sandstone and shale outcrops of the surrounding Murrees, was known to earlier investigators as the "Great Limestones" (MEDLICOTT, 1876). A newer investigation was carried out by WADIA in connection with his survey of the Poonch area (WADIA, 1928). The 100 km long mountain chain with elevations of 2000 m above sea level consists nearly exclusively of a hard, dense, mostly thin-bedded limestone. A secondary dolomitization can be noted in the lower and middle part, while the upper part is characterized by a marked silicification, with irregular silica nodules and bands. Fissuring and some fracture cleavage are frequent, resulting in a peculiar facetted weathering surface. The limestone is at least 500 m thick, but its normal base is not known. It has not furnished fossils, nor does it contain any trace of organic fragments. Locally, WADIA was able to discover in the basal part normal intercalations of the well-known Agglomeratic Slates of Kashmir-Pir Panjal type, which elsewhere contain an Upper Carboniferous fauna. Based on this discovery WADIA suggests a *Permo-Carboniferous* age for the limestones (also called Jammu limestones).

The limestones are unconformably overlain by nummulitic shales and limestones of *Eocene age*, which are locally preserved as a thin skin covering the older rocks. The nummulitics often show a base of bauxitic clays or carbonaceous shales, locally with thin coal seams.

In some places the Jammu limestones are intruded by serpentinized dunites in the form of dykes and stocks.

Structurally, the limestones form broad open anticlines which at their ends plunge rather steeply under their Murree cover. No inverted features are known on the surface, but steep faults can be observed on the southern side,

partly coinciding with the marked strike faults and steep thrusts bordering the Murrees against the more southern Siwalik belt (Jammu fault). If, and how far, the Jammu limestone range is actually thrust southwards cannot be decided at present. The coincidence of the recent topography with the tectonic outline of the range suggests a rather young latest uplift.

Of major interest is the *correlation of the Jammu limestones* with other areas. In the west we find comparable formations in the Hazara Mountains, where thick unfossiliferous limestones (Hazara limestones) are underlain by tillitic boulder beds. Eastwards, the Jammu limestone could be compared with the unfossiliferous Krol limestones (see later) of the Simla area. In all these limestone formations the lack of fossils is still a puzzle. Assuming a Permo-Carboniferous age, one should be able to compare them with the northwards-outcropping *Productus* Shales and the Zewan Limestones. The highly fossiliferous *Productus* Limestones of the Salt Range occur in a southern belt. The fossiliferous northern facies belt crosses the main Himalayan range, but from the Jammu area to the southeast the Lower Himalayas are characterized by sediments with a conspicuous lack or scarcity of fossils—an unfortunate fact persistant practically all along to the east of end the Himalayas. How far the fossiliferous Upper Palaeozoic deposits of the Salt Range do extend in an eastward direction is unknown. The old alignment of the western syntaxis may have formed an eastern limit. The Jammu limestone hills already lie on the eastern side of the syntaxial spur.

HIGHER HIMALAYAS OF THE PUNJAB

A well-outlined Higher Himalaya, the actual backbone of the Himalayan range, is hardly developed in the western Punjab Himalayas. From the geological map (Pl. I A) we can deduce how the sedimentary Kashmir basin extends towards Kargil and connects with the northern sedimentary basin striking from Spiti in a northwest direction. The intervening crystalline range plunges northwestwards towards the Kashmir basin and rises again further to the northwest on approaching the western Himalayan syntaxis, turning northwards and then towards the northeast. It is in this NNE-trending crystalline range that we find the highest elevation of the whole western Himalayas — the 8125 m high *Nanga Parbat*, which, with its excellently exposed migmatitic and granitized rocks deserves our special attention.

We have already noted how the older Palaeozoic and the Gondwana sediments with the Panjal Traps follow the Himalayan syntaxis, being overthrust by the metamorphic Salkhala and Dogra slates (Fig. 20). The Salkhalas continue northwards and then to the NNE in a tightly folded steep belt, becoming more and more metamorphosed, and culminating in the magnificent *uplift of the Nanga Parbat*. This steep belt of metamorphic rocks, forming a direct continuation of the western Himalayan syntaxis and abutting, with intervening ophiolites of the Indus suture line, against the ESE-WNW-striking Karakorum, is one of the most puzzling features of the Himalayan range.

Nanga Parbat

The Nanga Parbat, for many years a *reservation* for German mountain conquest, has been thoroughly investigated by PETER MISCH. His studies on the metamorphism and the metasomatic granitization of the Nanga Parbat have become classics in petrological geology, and are of the greatest importance, not only for the genesis of some crystalline rocks of the main Himalayan range, but for similar granitization problems in many Alpine and older ranges (MISCH, 1935, 1936, 1949).

Within the metamorphics of the Nanga Parbat area two original formations are recognized: *the Salkhalas*, black slates and phyllites with marble intercalations, and overlying them a thick section of *basic lavas*, tuffs and noritic intrusions. The Precambrian Salkhalas of the Nanga Parbat region must have been originally very thick. To this must be added an intense folding and a marked foliation which masks the original bedding. The foliation is parallel to the isoclinal folds which are drawn out in the foliation direction. In the less metamorphosed sections SSE of the Nanga Parbat a total (including isoclinal folding) of nearly 10 km of Salkhalas are exposed.

The contact with the overlying *volcanics* is sharp but conformable, in spite of the large hiatus from Precambrian to uppermost Cretaceous-Lower Eocene. This latter age has been assigned to the volcanics by WADIA (1937). Folding and foliation is the same as in the Salkhalas, and this fact in itself indicates that *only one major orogeny* is responsible for the metamorphism and granitization of the Nanga Parbat region. MISCH stresses the fact that *no relics of an older metamorphic phase are known*, and also that diaphthoritic processes must have been absent.

Normal volcanics are present in the southeast area (Fig. 21) where basaltic to somewhat more acidic lavas overlie tuffs and tuff breccias together with tuffaceous, calcareous argillites. They belong to the volcanic Indus Flysch facies, to be described with the northern Punjab Himalayas. Contemporary with or slightly younger than the volcanics are intrusions of norites, hypersthene

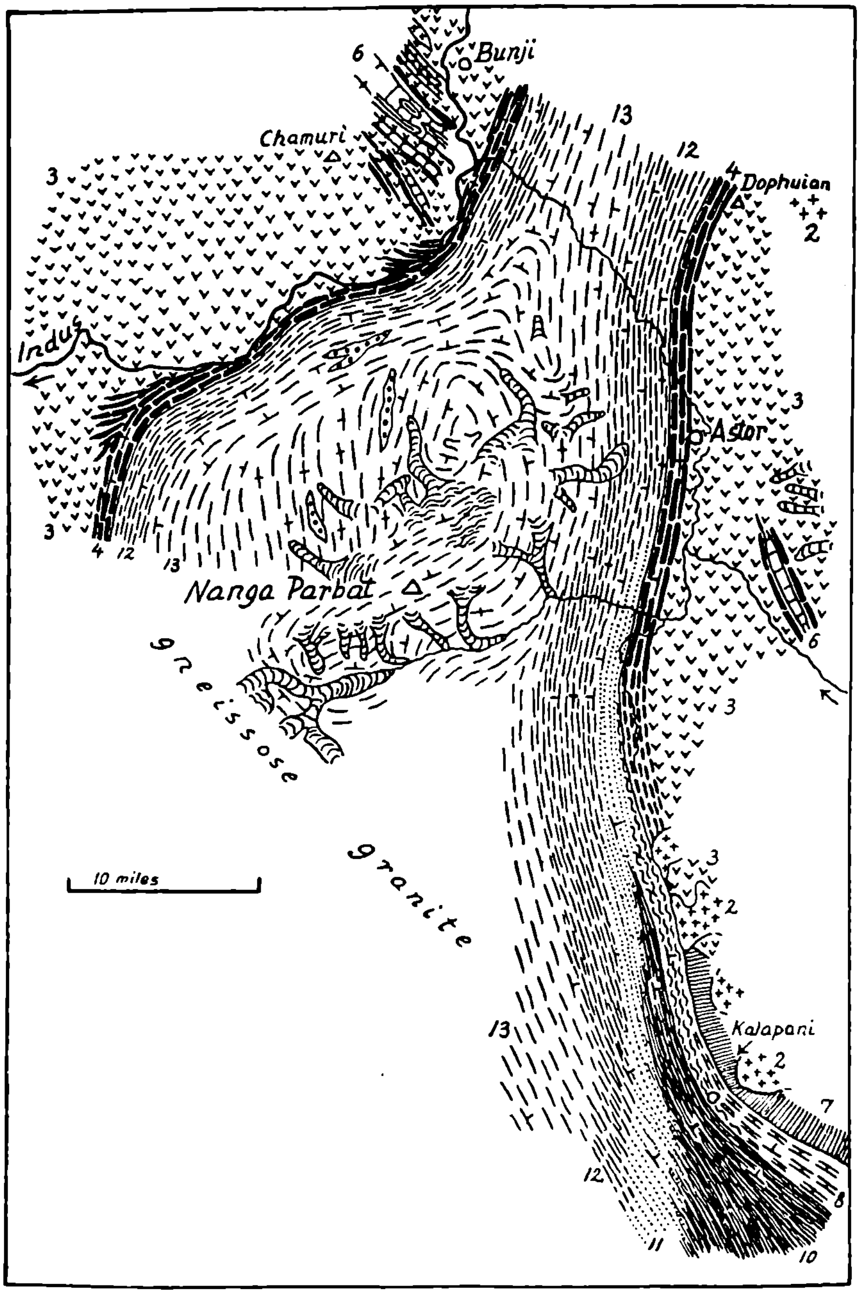


Fig. 21 *Geological sketch map of the Nanga Parbat region,* NW Himalaya; reproduced from P. Misch (1935)

1 tourmaline granite; post-orogenic (dotted)
2 quartz-diorite and granodiorite; post-norite
3 norite, hypersthene diorite, etc.; widely altered to metanorite and metadiorite; Eocene
4 mesozonal amphibolite } synorogenic-metamorphic norite, etc.
5 epizonal greenschist
6 marble and schist zones in norite, metanorite, etc.
7 basaltic and more acidic lavas } Cretaceous-Eocene volcanic formation
8 variegated tuff breccias and tuffaceous-calcareous argillites
9 tuffaceous argillaceous rocks (8) epizonally metamorphic } metamorphism and granitization synorogenic
10 Salkhala group; dark slates and phyllites with subordinate thin limestone and greenstone bands
11 non-granitized schists; chiefly mesozonally metamorphic Salkhalas
12 mesozonal migmatitic gneisses (chiefly augen gneisses and banded gneisses); incompletely granitized Salkhalas
13 migmatitic granitic gneiss; granitized Salkhalas (11)-(13) contain intercalations of schists, marbles, and amphibolites; mesozonal in (11) and (12), katazonal in (13)

diorites and locally dunites. They too belong to the *Indus ophiolitic belt* and are widespread in the northern Nanga Parbat area, where they border the steep gneisses on the west and east sides. Northwards, the volcanics and their related intrusives become gradually more metamorphic, in line with an increase of metamorphism of the Salkhalas. This fact is well shown on MISCH's sketch map (Fig. 21). The sharp and vertical contact between the ophiolitic rocks and the more or less altered Salkhalas is suggestive of a *major disturbance*. I see in this tectonic line the syntaxial equivalent of the *Indus suture*, bordering the ophiolitic geosynclinal zone from the main Himalayan series. This Indus suture line would run from south to north on the east side of the Nanga Parbat central uplift, turn around the northernmost syntaxis at the south side of the Karakorum, geologically a still highly obscure area, and then turn southwards along the west side of the Nanga Parbat metamorphics. Along this major tectonic line a considerable amount of post-Precambrian sediments has been cut out tectonically, but it is reasonable to assume that towards the western Himalayan syntaxis, which reflects a rejuvenated Gondwana and probably even much older cross-high, a regressive overlap set in, reducing successively the sedimentary cover in the neighbourhood. Along this reduction belt the conditions favouring major tectonic disturbances were set, resulting in the present syntaxial picture.

Coinciding with this tectonic line, though possibly not directly related to it are some results of observations by FINSTERWALDER made during his triangulation work in the Nanga Parbat region (FINSTERWALDER, 1935). From trigonometric surveys for the determination of precise elevations it was possible to determine the deviation of the plum-bar. On two stations, west and east of the Astor Valley, through which the contact between volcanics and gneisses runs in a north-south line, opposing deviations were observed. In spite of the great height of the Nanga Parbat massif which surpasses by about 3000 m the mountains to the east, the deviation east of the border zone was five times larger and opposite to the deviation of the west side (54″ to the east as compared to 10″ to the west). The difference is explained by the higher specific gravity of the basic volcanics underlying the eastern station as against the lighter gneisses to the west. This explanation has certainly its merits, but a more deep-seated cause, reflecting the eastern border of the Himalayan syntaxis, could also add to this anomaly (the situation is shown in Fig. 22).

The bulk of the original Nanga Parbat sediments consisted of Salkhalas, and their predominantly argillaceous composition allows a unique study of the gradual metamorphism and subsequent granitization of an argillaceous sequence. The central granite gneiss core of the Nanga Parbat has by some authors been regarded as resulting from magmatic intrusions, a general view held for many crystalline mountain massives. However, MISCH's careful investigations have proven, at least for the Nanga Parbat region, that the granite gneisses were formed by progressive granitization. The great interest in this mountain range is the fact that all stages from low-grade metamorphism to extreme granitization are excellently exposed in fantastic cliffs over 5000 m high and extending for many kilometres.

MISCH distinguishes three major zones:

1. An outer sedimentary zone with a progressive metamorphism.
2. An outer granitization zone.
3. An inner granitization zone.

All zones are generally steeply dipping or vertical. The metamorphic isogrades are equally steep.

1. In *the outer sedimentary horizons* the Salkhalas change within the *Epizone* from black carbonaceous slates through phyllitic slates, phyllites with some rotated albite porphyroblasts into garnetiferous phyllites and muscovite-garnet schists. In the lower *Mesozone* biotite appears in muscovite-biotite schists, partly with rotated almandines and some oligoclase. Garnet gneisses and kyanite schists occur in the higher Mesozone, with an increase of biotite over muscovite and

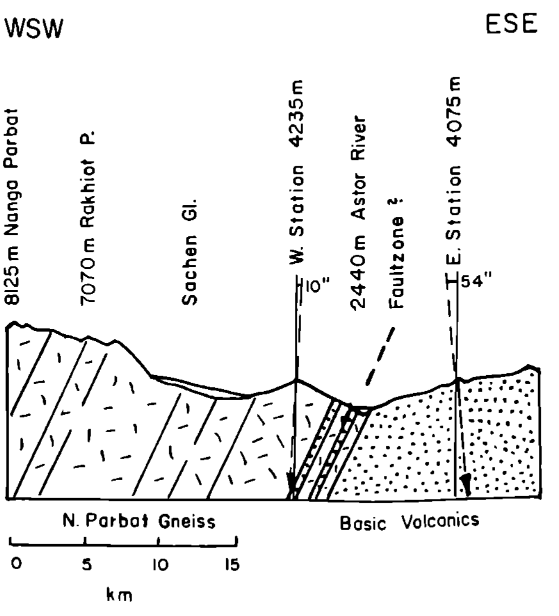


Fig. 22 *Deviation of the plumbar E of Nanga Parbat*, showing influence of basic rocks and possibly major tectonic disturbance; redrawn after R. FINSTERWALDER (1935)

some orthoclase in the gneisses. In the *Katazone* sillimanite gneisses replace the kyanite schists, the orthoclase increases and biotite is dominant in the frequent biotite gneisses. Carbonaceous matter is still present in the Katazone, and granitization is rare in this outer zone in spite of the kata character of the argillaceous rocks. It could be argued that too much bituminous matter in the outer Salkhalas retarded the granitization process. This idea would only hold if the original composition of the inner Salkhalas, where granitization is present, was originally poorer in bituminous matter. This has unfortunately not been investigated. A selective retarding action of bituminous matter during metamorphism is known elsewhere, but is still little understood.

2. *The outer granitization zone* exposes an incipient granitization, which begins in the higher Mesozone. Within the kyanite-bearing schists single porphyroblasts of microperthitic orthoclase develop, evenly distributed or enriched in layers. No granitization begins in the Nanga Parbat region before a higher Mesostage has been reached. An increase of feldspars leads to more massive augen gneisses—actually porphyroblastic gneisses or banded gneisses which often contain microcline. Between such granitic gneisses one can still observe zones with kyanite-biotite schists, which shows that the metamorphism producing the kyanite schists antedates the granitization. Misch thinks that for the feldspar-rich rocks an introduction of potash was necessary, entering as hot solutions. Lacking detailed chemical analyses, this question cannot be answered and must be left open. Under a beginning mobilization, selective granitization leading to banded gneisses could depend on minor primary differences in the argillaceous material, and also for the regularly distributed feldspar porphyroblasts the introduction of solutions from a more remote source is hardly necessary.

3. The *inner granitization zone* forms the central uplift of the Nanga Parbat. The sharp borders of the banded gneisses disappear. Fine-grained biotite gneisses have been replaced by coarse biotite flaser gneisses of granitic appearance. The general aspect of these gneisses is that of a very irregular composition, with schlieren and indistinct banding, local concentrations of biotite zones and the frequent presence of garnets (almandine). In the main rock, orthoclase and oligoclase andesine occur with quartz and biotite and often primary muscovite. The almandine can be locally enriched. The granitic gneisses show a crystallization foliation but are free from cataclastic alteration and deformations; the texture is still crystalloblastic. The *migmatitic* aspect is manifest and many features indicate a stronger granitization of rock types of the more marginal zones. Most distinctive are katazonal fine-grained bands of paragneiss with gradational borders against the granitic gneisses. Such intercalations are very thin, but can be followed for great distances, and are partly interrupted by an increase in granitization. Of particular interest are thin *marble layers with associated lime silicate bands* which form conformable intercalations in the granite gneisses. They are not more than 20-30 m thick, but can be traced for many kilometres. The absolute proportion of the marbles is nearly the same as in the unmetamorphic Salkhalas of the border zones. This highly interesting fact shows that while the argillaceous rocks have been fully granitized, the carbonates were spared and show only a katazonal metamorphism.

The gradual granitization from the border zones to the inner core, the inhomogenity of the granitic gneisses and the preserved thin carbonate bands all suggest an *in situ granitization* and not a magmatic granite intrusion for the main mass of the Nanga Parbat. It is hardly conceivable that a granitic intrusion, liquid or semiplastic, could have spared such thin marble bands, which still conform in their strike to the general structural pattern. In this connection one should further stress the fact that the metamorphism and subsequent granitization does not only increase *across* the strike, but also *along* the strike (from south to north) and that all changes can be observed practically along one and the same horizon. In the case of the marble zones, one can follow them along their strike noting only minor changes, while the surrounding argillites change from slates to granitic gneisses.

Representing the latest, and clearly post-orogenic phase in the Nanga Parbat granitization are the small but still conspicuous white, mostly fine-grained tourmaline granites, grading to tourmaline-bearing aplitic granites (Fig. 23a, b). These homogeneous granites are absolutely massive and cut discordantly through the gneisses of the Inner Zone. Apart from larger lenticular masses they form a complex system of dykes and smaller veins. Corresponding pegmatites contain large, often parallel-aligned, black tourmalines. The mode of emplacement and the fresh, undisturbed aspect of the tourmaline granites clearly shows that we have here very late intrusions. They could be explained as *fully mobilized material* related to the extreme granitization which moved independently and began to intrude locally. As we will see later, post-orogenic young tourmaline granites are very frequently met all over the Himalayan range where crystalline rocks occur and where their genetic relation as end-products of an extreme granitization is generally manifest.

Concluding Misch's observations of the Nanga Parbat, one of the most striking features reported are the *intimate relations of a progressive metamorphism with a synkinematic granitization.* We have already

noted that granitization begins invariably only after a higher Meso stage of metamorphism has been reached, and that a higher grade of granitization depends on a Kata metamorphism. All evidence in the Nanga Parbat indicates that metamorphism and granitization are clearly a careful comparison of bulk analysis of the original rocks with all intermediate stages and the granitized end products, a most important project for future investigations.

One fact, however, seems clear: *that the rise in temperature, responsible for the metamorphism and*

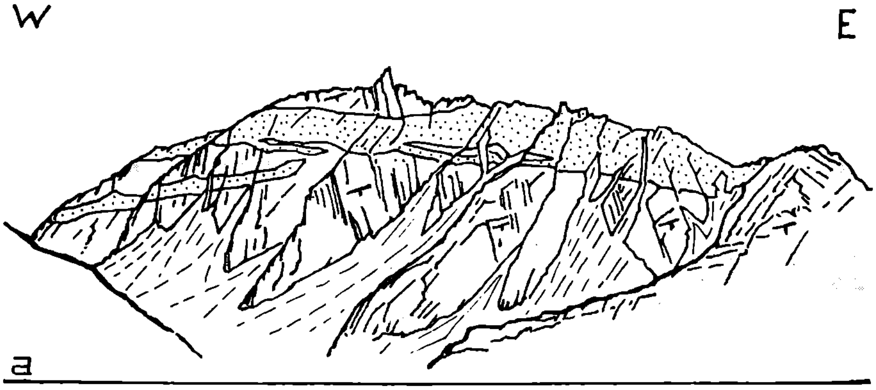


Fig. 23a *Tourmaline-granite cutting gneiss at Jalipur Peak,* NW Nanga Parbat; redrawn after P. Misch (1935)

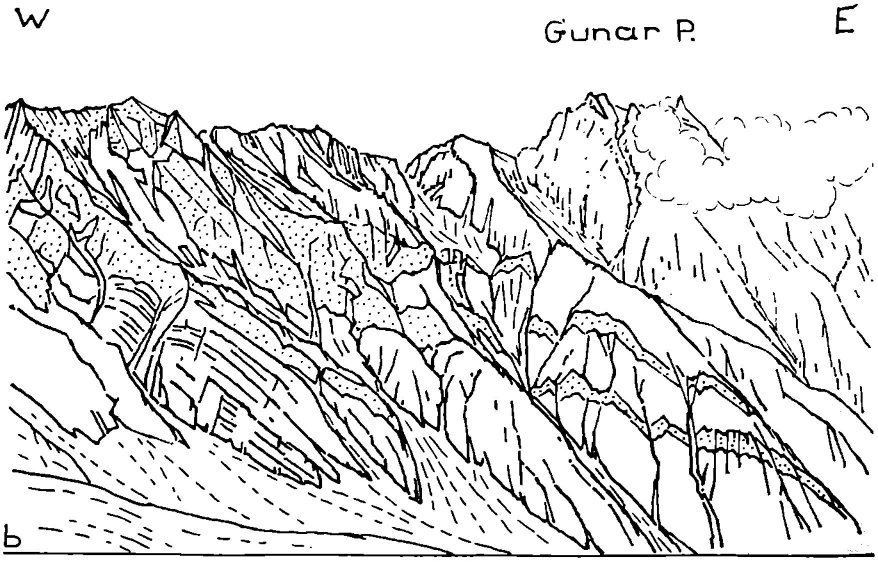


Fig. 23b *White tourmaline-granite in gneiss WNW of Gunar peak.* NW Nanga Parbat; redrawn after photo by P. Misch (1935)

function of an increasing temperature. Misch, however, believes that "rise of temperature and increasing infiltration of granitizing solutions go parallel". The importance of such *granitizing solutions* is still highly problematic. I believe that locally mobilized solutions (rich in water) can infiltrate their surroundings, but that their reaction is only very local, i.e. they are not intruded from a deeper and more distant source. How far such a possibility is acceptable for Nanga Parbat can only be ascertained by a *granitization is unrelated to depth of burial.* The metamorphic isogrades are now practically vertical. The necessary rise of temperature must have come originally from below. One may think of a heat front or, following Wegmann (1935), of a rising migmatic front. This problem is not restricted to the Nanga Parbat, but to the progressive metamorphism in many other parts of the Himalayas. The Nanga Parbat example clearly shows that vertically, and this over a span of 7000 m, no change in rock behaviour

can be noted. The vertical layers show a constant composition; the metamorphism increases along the strike in a lateral direction towards the centre of the massif. This means that an overburden of 7000 m does not alone affect the underlying rocks, while an introduction of heat immediately causes metamorphic changes. Epimetamorphic stress effects are all that an overburden

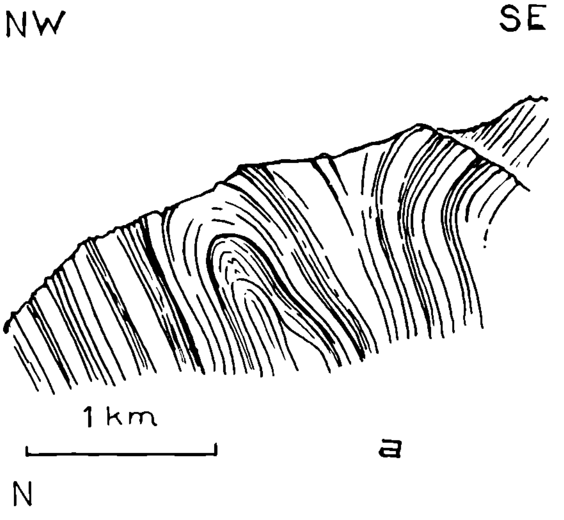


Fig. 24a *Steep folds in gneiss of the Lichar ridge.* Northern Nanga Parbat; redrawn after P. Misch (1935)

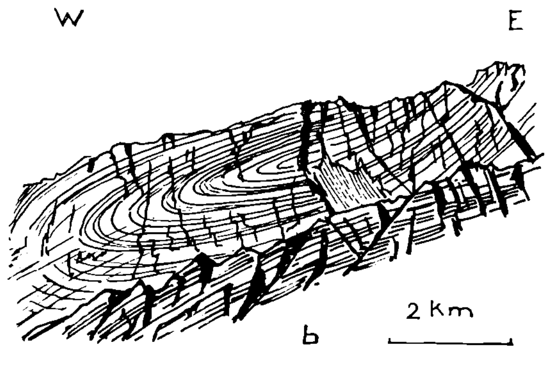


Fig. 24b *Huge overlying fold in gneisses of Purais peak.* North of Nanga Parbat; redrawn after P. Misch (1935)

even of great magnitude can produce in the underlying rocks. This idea, in my opinion, seems applicable also in the major Alpine culmination which exposes kata metamorphism and related granitization. Many Alpine authors still place too much emphasis on the effect of great overthrusts on underlying rocks. The Himalayan examples show clearly enough that also the great Meso to Katazonal Alpine Ticino culmination was affected by a heat front introduced from below as suggested by Wenk (1962) and not by overburden of higher nappes for which in this particular alpine section our newest results give little support.

The internal structure of the Nanga Parbat massif is shown in general lines on the sketch map (Fig. 21). Very steep beds dominate the tectonic picture, characterized by an intense isoclinal folding on a smaller scale. A structural analysis of these minor but widespread folds has not yet been made, but from Misch's description one can deduce that most of the folding is strictly south striking, parallel to a pronounced foliation.

Intercalated amphibolitic zones and particularly remarkable marble bands expose an intricate flowing-type folding. On a large scale, and mostly concentrated in the more interior part of the massif, occur some schlingen-type folds with steep axes (Fig. 24 a, b).

We have already mentioned that the border region between the gneisses and the volcanic rocks corresponds to an important tectonic feature related to the Indus suture line. Towards this line and border zone, the little-metamorphosed basic rocks underwent a metamorphism coupled with a marked schistosity, resulting in mesozonal amphibolites.

The structures in the volcanics are mostly conformable to the regional picture, except in two areas where relics of folded Salkhala-type sediments with marble zones are found in the volcanics, exposing a structural pattern strongly contrasting with the Nanga Parbat zone. Misch (1935) describes the *Talichi sedimentary enclosure* in the Indus Valley north of the Nanga Parbat and the *Godai zone* southeast of Astor. Both are indicated in the sketch map (Fig. 21).

The Talichi sedimentary zone consists of Salkhala-type black slates, which have not yet reached the gneissic stage. The metamorphism is somewhat higher in the border zone and rather weak in the more central part. Intercalated thick layers of crystalline limestones form impressive folds, excellently exposed in the cliffs towards the Indus Valley (Fig. 25). The contact with the surrounding basic rocks is conformable, and in some of the border zones the argillaceous sediments disappear, and the limestones extend further into the basic masses. The ends of the marble layers show intricate minute flow folds at the contacts with the basic rocks (Fig. 26). As in the granitization zone within the Nanga Parbat, the carbonate rocks are more resistant to the invasion of the basic rocks than are the slates.

Of special interest is the *aberrant structural trend* of the Talichi sediments, which strike from NW towards SE, i.e. with a 90° angle against the northern Nanga Parbat gneisses and their contact zone. A similar abnormal trend can also be observed somewhat further down the Indus Valley where the metamorphic basic rocks of

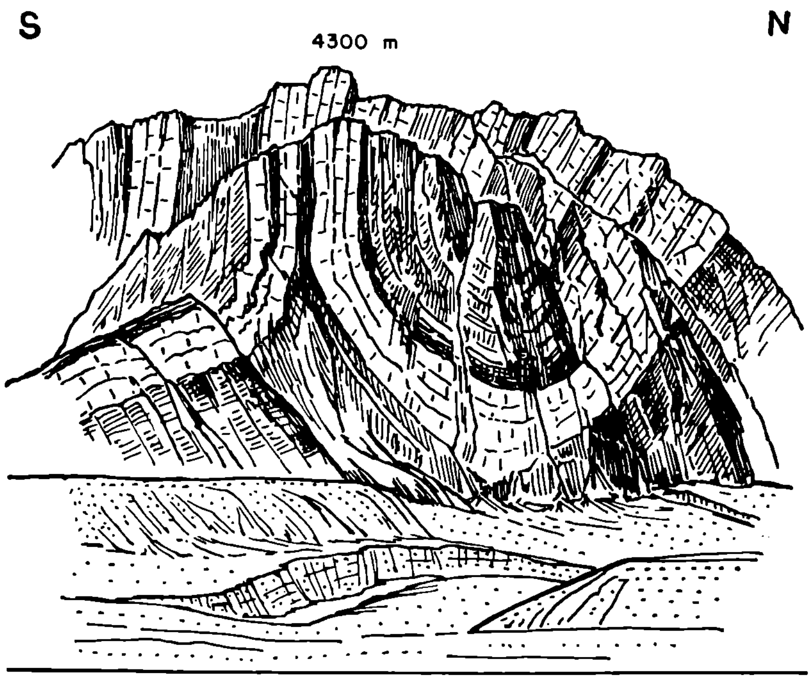


Fig. 25 *The sedimentary relic of Talichi,* Indus Valley, northern Nanga Parbat. The limestone marbles form large folds in black slates (Salkhala type) with abnormal strike direction (SE). Foreground terraces of Indus Valley; redrawn after P. MISCH (1935)

the border zone turn rather abruptly from a SW trend into a NW direction.

Other sedimentary inclusions outcrop along the Godai Valley, SE of Astor (Fig. 27), in the form of thick vertical marbles surrounded by basic rocks with a schistosity conformably adjusted to the marble horizon. Here too, the interior of the marbles shows an intense flowing pattern. The marble layers strike here towards SSE, while the border zone south of Astor is mostly N-S aligned.

These two examples seem to indicate that outside the main Nanga Parbat uplift, relictic Precambrian rocks show a structural pattern which does not conform to the regional outline of the syntaxial feature. The Godai marbles, however, seem more in line with the gradually changing trend from N-S into the SE-NW of the northwestern Kashmir region.

Some remarks may be added about the surprising *height of the Nanga Parbat,* which, west of the Daulagiri, is the only 8000 m mountain over a stretch of 1100 km of the Himalayas. The Indus Gorge just north of the range averages 1300 m above sea level, while the summit of Nanga Parbat is 8125 m. We find in the Nanga Parbat region indications of a *very young uplift* confirming a late morphogenic phase of the Himalayan range. MISCH (1935, 1936) discovered in the Indus Valley north of Nanga Parbat at *Jalipur,* young, only little-consolidated but steeply folded sand-

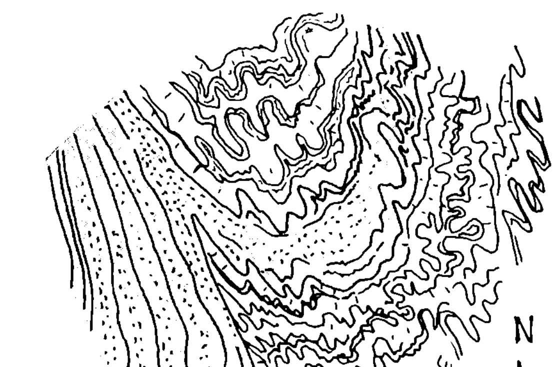


Fig. 26 *Detail of marble layer ending in basic rocks, southern Talichi zone* note intense flow features (marble = white, basic rock = grey); redrawn after P. MISCH (1935)

stones, turned up even to vertical dips. They are located along the border zone between the Nanga Parbat gneisses and the basic rocks, just where the major tectonic disturbance is supposed to pass. The sandstone transgresses the gneisses, and is therefore post-metamorphic and certainly considerably younger than the metamorphism—most probably a Pleistocene deposit. The sandstones contain only small pebbles, and the large boulders typical for the younger Indus gravels are not present. This may indicate that during the deposition of the young Jalipur sandstones the relief was considerably lower.

The Jalipur sandstones are transgressed by the Indus terraces, of which four to five major levels are still preserved. The present Indus River flows through the gorge north of the Nanga Parbat with a relatively wide, terraced valley bottom. It rarely cuts into bed rocks, but flows mostly over its youngest gravel fill. Above the present river follow three well-outlined terraces at 60 m, 120 m, and 170 m. A fourth level, less well preserved exists 450 m above the present river. A conspicuous planation can be observed in many side valleys at an altitude of 5000 m, i.e. 3700 m above the present valley bottom. In between, remnants of some lake fills occur, recognizable by their fine white sand deposits.

The folded Jalipur sandstones and the various terrace levels clearly reflect the *young morphogenic history* of this part of the Himalayas and coincide with the particularly marked uplift of the Nanga Parbat. The relation of glacial stages to the river terraces in the Nanga Parbat region is still uncertain. Surprisingly enough, earlier glacial stages have apparently not been very pronounced. No glacial relics are known below 2500 m above sea level, while some of the present glaciers reach the 3000 m limit, and one from the steep south flank of the Rupal Valley ends at 2900 m and far below the tree line (Nanga Parbat map of FINSTERWALDER, 1936).

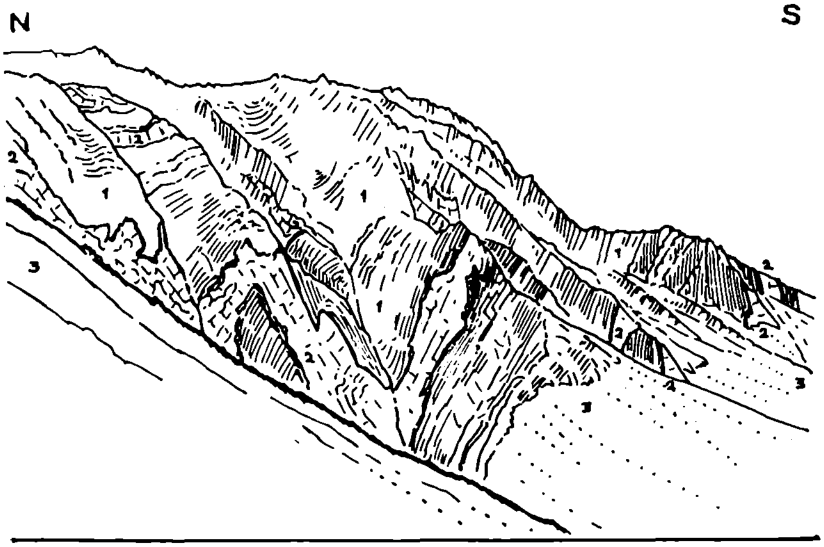


Fig.27 *Marble zones in basic schists north of Godai,* SE Astor, Nanga Parbat region; redrawn after photo by P. MISCH (1935)

1 basic schists 2 marbles 3 scree

Eastern Higher Himalayas of the Punjab

A direct connection of the Nanga Parbat Range with the crystalline backbone corresponding to the High Himalayas of the eastern part of the Punjab does not exist. Here the Kashmir basin intervenes, and only at its eastern end, where it rises in a complicated pattern of spurs and narrow embayments towards what is geologically, but not morphologically, the corresponding range to the High Himalayas, is there a beginning of the regional trend which is so clearly outlined through most of the Himalayan range. We have already seen that the fossiliferous sediments of the Kashmir region cross, with only minor relics, the High Himalayas and continue in a SE-directed wide sedimentary belt into the famous Spiti region. South of the crystalline divide we find sediments of the Lower Himalayas, distinct from the Kashmir basin and characterized by a surprising lack of fossils. They will be discussed in detail when dealing with the Kumaon Himalayan section.

Little is yet known of the large crystalline uplift following east of the Kashmir basin and lying northeast of the Jammu region. Granitic

rocks and granite gneisses are known to extend continuously over 240 km and outcrop intermittently within the metamorphics south of the Spiti region and along the Sutlej River which limits the Punjab from the Kumaon Himalayas. Garnetiferous mica schists and kyanite-staurolite schists form the main metamorphic rocks, intruded by biotite granites. In this eastern area, severe tectonics affect the crystalline rocks and lead to the crystalline klippen as seen in the Simla area, which belong most probably to larger thrust sheets with displacements of up to 100 km (BERTHELSEN, 1951). The metamorphics include older (probably Precambrian) but also possibly younger rocks, and some of the metamorphism and granitization may be coincident with or even later than the main thrusting, a fact of great significance in the Himalayas.

The age of some granites south of the Spiti region is still most uncertain. HAYDEN (1904) mentions granite intrusions into the Cambrian in the Sutlej Valley, while granite intrusions in the more northern regions (Rupshu, to be discussed later) vary from Permian to Eocene age. HAYDEN also mentions a biotite granite pebble from the Permian conglomerates in the Spiti River, indicating a pre-Permian age for at least some of the granite intrusions. In this connection AUDEN (1933) discusses the age of some Himalayan granites of the adjoining Kumaon region, based on the find of a small granite pebble in the so-called *volcanic breccias*, placed into the Mandhalis (old Palaeozoic). Similarly, arkoses from the Jaunsars and Tal formations are regarded by AUDEN as derived from older granitic rocks. A certain coincidence of the presence of such older granites with abnormal Aravalli trends within this part of the Himalayas is mentioned by AUDEN, and this statement merits our full attention and will be discussed in a later chapter. The fact that otherwise granitic and metamorphic pebbles are very rare or practically absent in most of the pre-Tertiary clastics of the Himalayas is of particular significance and will be dealt with when discussing the regional metamorphism of the Himalayan range.

TIBETAN OR TETHYS HIMALAYAS OF THE PUNJAB

We have already mentioned that this section embraces only the easternmost part of the Punjab Himalayas, with the famous *Spiti area* as its prime representative. The Tethys sediments of the Kashmir basin, where they intermingle with the Gondwanas of the Lower Himalayas, do not allow such a clear-cut division for the western part. The term Tibetan Himalayas should not be taken too literally, since large tracts of this northern part of the Himalayan chain are not in Tibetan territory. On the other hand, by no means all the rocks found in this northern belt are of the Tethys type of deposits. The writer prefers therefore to use the term Tibetan Himalayas for this northern region, meaning the part of the Himalayas north of the main range which slopes into or towards Tibet.

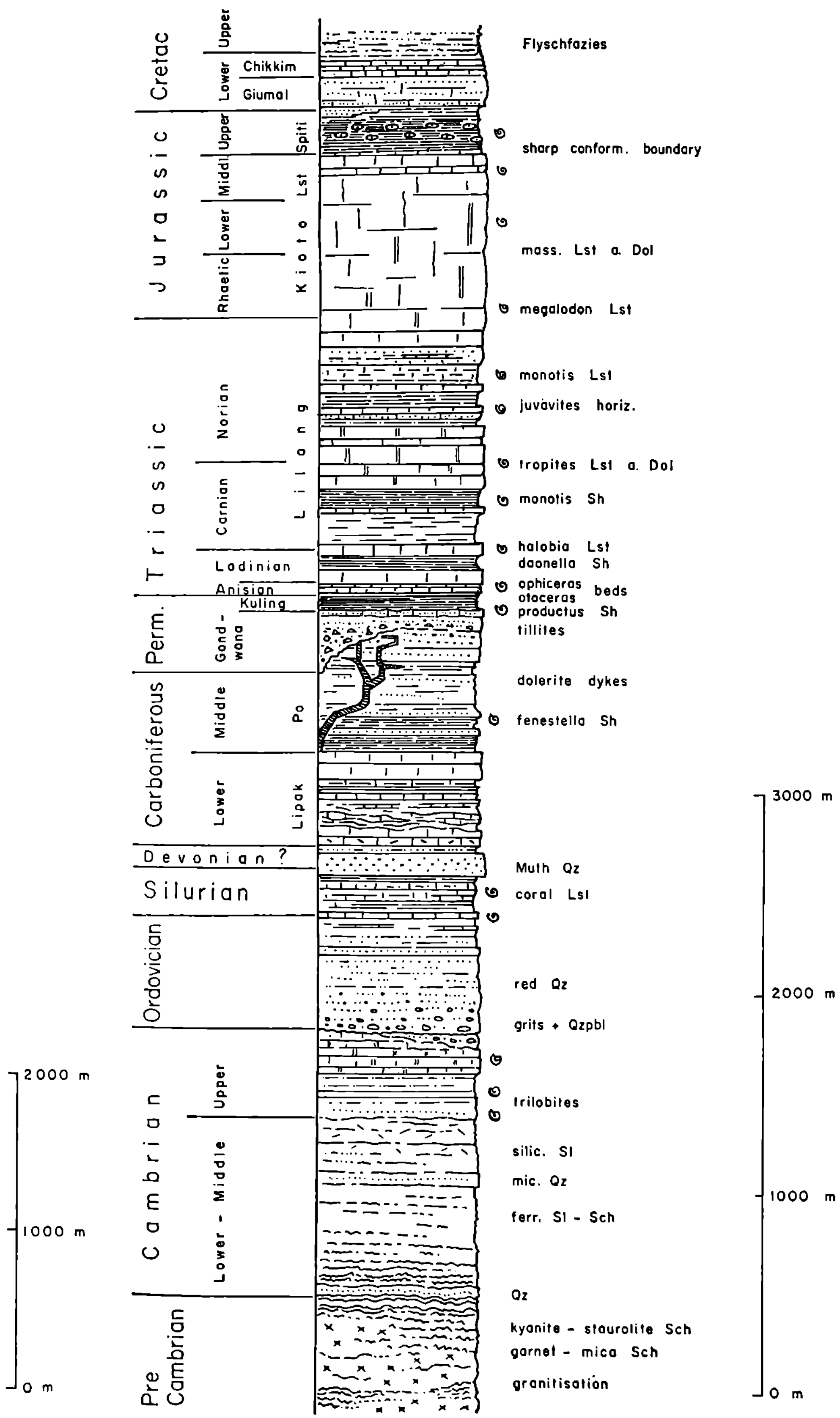
Spiti region

Covering the crystalline rocks of the Higher Himalayas follow the sediments of the wide basin, which, in its eastern part, is crossed by the Spiti River, a western tributary of the Sutlej. The general situation has been schematically illustrated by BERTHELSEN (1951). *The metamorphics of the Higher Himalayas form the normal base of the thick sediments which range from the Cambrian to the Cretaceous.* The richness in fossils and the nearly continuous well-exposed sections have made the Spiti region world-famous. HAYDEN (1904) has given a well-illustrated compilation of the Spiti section, while the actual Jurassic ammonite fauna of the Spiti Shales was described as early as 1865 by STOLICZKA. Surprisingly enough, this world-famous section has never received a modern investigation and remains still a prime challenge for a detailed stratigraphical study.

We cannot here enter into great detail regarding the stratigraphy of the Spiti region, but some of the more salient features of regional importance are discussed. It is this conformable sedimentary sequence of Spiti, from Precambrian onwards, which reflects *a calm epeirogenic pre-Alpine history* of the "Tibetan" Himalayas. For easier reference, a stratigraphical section giving the approximate average thickness of the various formations has been compiled from all the available information (Fig. 28). We refer to this in the following.

We have already seen that the base of the sedimentary column in the Spiti region is formed by argillaceous metamorphics, where mica schists, more or less rich in kyanite, staurolite and garnets are predominant. A granitization of these schists results in granitic horizons, the age of which is still disputed. Similarly, some of the argillaceous metamorphics represent a metamorphic facies of rocks of probable Cambrian age. The oldest non-metamorphic sediments consist of ferruginous clay slates, pinkish quartzites with intercalated grits which form surprisingly constant horizons. They are followed by black, purple and grey slates, and green and red quartzites. The rusty ferruginous slates are a

Fig. 28 *Stratigraphy of the Spiti area;* compiled mostly after HAYDEN, WADIA, PASCOE and others


Cretac
Upper
Lower
Chikkim
Giumal
Jurassic
Upper
Middl
Lower
Rhaetic
Spiti
Kioto Lst
Triassic
Norian
Carnian
Lilang
Ladinian
Anisian
Kuling
Perm.
Gondwana
Carboniferous
Middle
Lower
Po
Lipak
Devonian ?
Silurian
Ordovician
Cambrian
Upper
Lower - Middle
Pre Cambrian
Flyschfazies
sharp conform. boundary
mass. Lst a. Dol
megalodon Lst
monotis Lst
juvavites horiz.
tropites Lst a. Dol
monotis Sh
halobia Lst
daonella Sh
ophiceras
otoceras
beds
productus Sh
tillites
dolerite dykes
fenestella Sh
Muth Qz
coral Lst
red Qz
grits + Qzpbl
trilobites
silic. Sl
mic. Qz
ferr. Sl - Sch
Qz
kyanite - staurolite Sch
garnet - mica Sch
granitisation
2000 m
1000 m
0 m
3000 m
2000 m
1000 m
0 m

characteristic landmark in this region. Upwards the slates become more siliceous, are highly cleaved, forming pencil slates, and grade into micaceous quartzites. Here carbonate rocks set in, as dolomites and micaceous quartzitic limestones. In the latter appear the first fossils, such as *Lingulella* and badly preserved trilobites. Intercalated quartzites expose a great variety of fossil tracks. Based on higher trilobite horizons in slaty beds, a *Middle* to *Upper Cambrian age* has been suggested for this sequence.

The uppermost dolomitic limestones of the *Cambrian section* expose a striking facies change and become locally conglomeratic, with large dolomite and quartzite boulders, mostly derived from the surrounding deposits. Violent local contemporary erosion must have occured, probably of a very short duration since conglomerates as well as dolomites are covered by thin, dark siliceous carbonatic slates, terminating the Cambrian below the Ordovician disconformity.

Covering the Cambrian slates, deposits of Ordovician age start with a conspicuous clastic formation, beginning with a marked conglomerate with boulders of Cambrian dolomites and quartzites up to 30 cm, followed by grits and a second conglomerate with a predominance of quartzite pebbles. They grade upwards into grits and eventually into the thick red quartzites which give this section its characteristic aspect. The basal contact is mostly disconformable, transgressing on a partly eroded Cambrian surface. Locally unconformable contacts are present (Fig. 29) but regionally the conglomerates are *conformable*.

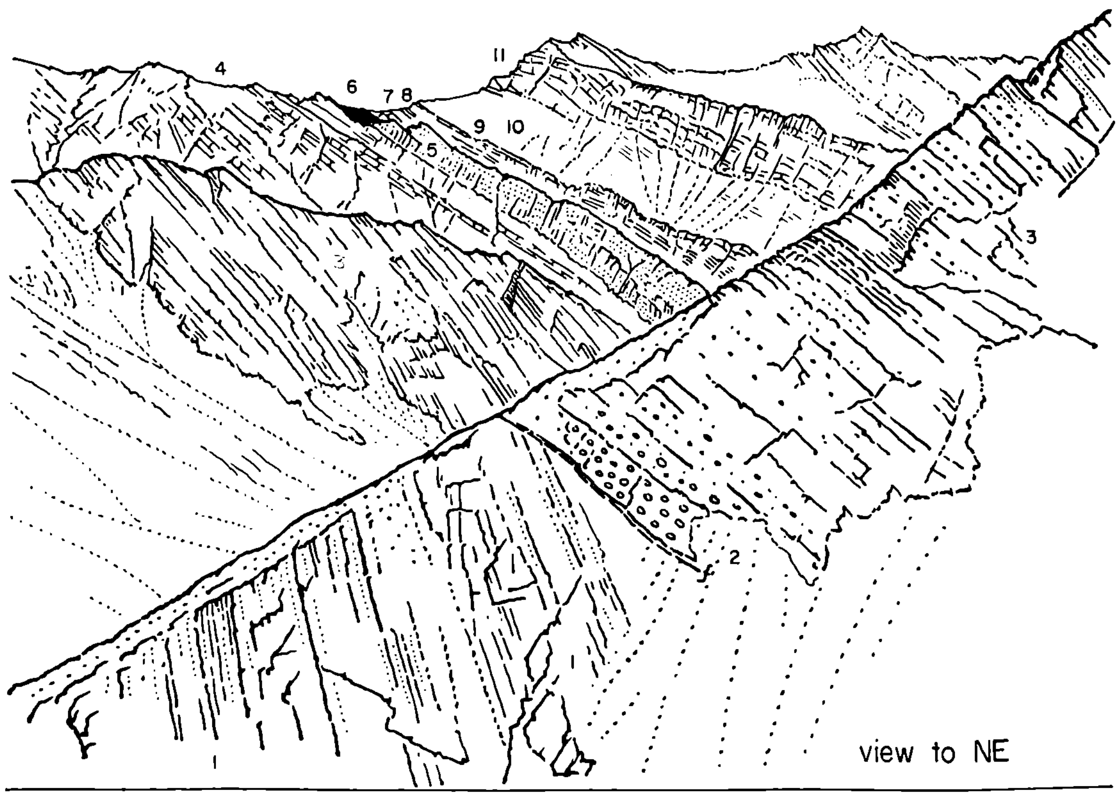


Fig. 29 *The Paleozoic and Mesozoic series near Muth*, Spiti area; drawn after photo by H. H. Hayden

1 Cambrian slates and quartzites
2 basal Ordovician conglomerates (faulted contact)
3 Ordovician grits and quartzites
4 Silurian limestones
5 Muth quartzites
6 Productus shales
7 *Muschelkalk*
8 *Daonella* shales
9 *Daonella* limestones
10 grey shales (U. Triassic)
11 *Tropites* limestones

The quartzites are covered by slates and thin-bedded limestones, increasing upwards. They are highly fossiliferous, with faunas of Ordovician and Silurian age. Red crinoidal limestones form the upper part of the Silurian deposits (Fig. 30).

A very conspicuous horizon in the Spiti area, as in most of the northern Himalayan sections, is the hard, mostly massive, white *Muth quartzite*

which we have seen already in the Kashmir basin. It overlies the Silurian conformably and is covered, again without any sign of stratigraphical or structural break, by siliceous shales, thin quartzites and limestones with a Lower Carboniferous fauna—the Lipak formation. Higher in the section a more shaly sequence corresponds to the Middle Carboniferous Fenestella Shales, here called the Po formation. Doleritic dykes are all along the northern Tibetan Himalayas. Frequently the black shales follow conformably but with a strikingly sharp contact directly above the white Muth quartzites. There is no trace of the missing Devonian and Carboniferous horizons or the otherwise constant tillitic conglomerate levels (Fig. 31). The same condition is the rule in most parts of the Kumaon Himalayas, as we will see in the next chapter.

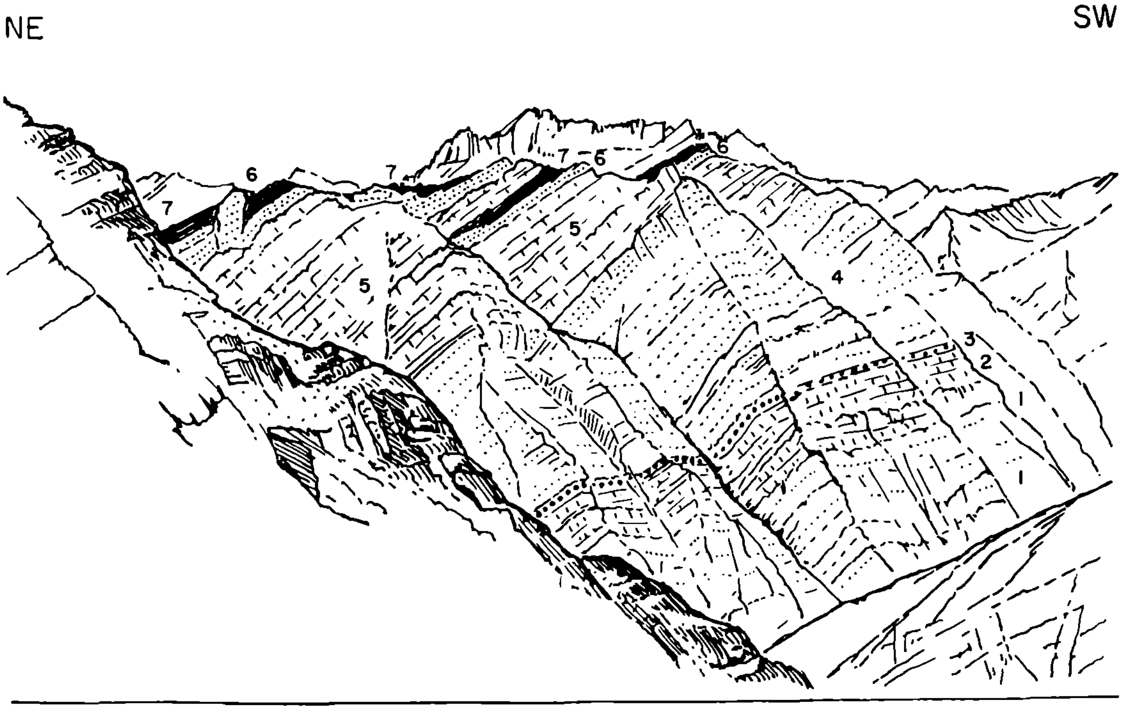


Fig. 30 *Paleozoic section between Parahio and Piu rivers,* Spiti region; drawn after photo by H. H. Hayden

1 Cambrian slates and quartzites
2 Cambrian dolomites
3 Ordovician basal conglomerate
4 Ordovician-Silurian quartzites
5 Silurian limestones
6 Muth quartzites
7 *Productus* shales

frequent in this section. Upwards clastic sediments increase, and where the sequence is best developed, as in the more eastern part of the Spiti area (Lipak River), dark silty shales contain irregular grits with unsorted pebbles and boulders up to 30 cm in diameter. This horizon could be compared to the tillitic *Blaini boulder beds* of the *Upper Carboniferous.* Westwards, the base of the boulder beds and conglomerates becomes more and more unconformable and cuts down to successively lower horizons, locally even down to the Ordovician red quartzites. Upwards, the conglomerates are overlain by thin, fossiliferous calcareous limestones with a Permian fauna, followed by the conspicuous black Permian Productus Shales—the most constant marker horizon

Overlying the Permian *Productus* Shales there follows absolutely conformably and in apparent stratigraphical continuity, the Triassic deposits. Thus, the Spiti area as well as many other sections in the northern Himalayas is the classical ground for a careful investigation of the Palaeozoic-Mesozoic boundary. As in the Kashmir region, the lowest Triassic beds are a brown *Otoceras* limestone. The find of a few specimens of *Productus* in these beds in Kashmir (Bion, 1914) demonstrates that they mark a passage from the Permian into the Trias. A comprehensive table of the famous Spiti Trias is given in the *Lexique Stratigraphique Asie*, Vol. III, 1957.

No sharp limit can be drawn between the Uppermost Trias and the Lias, which together

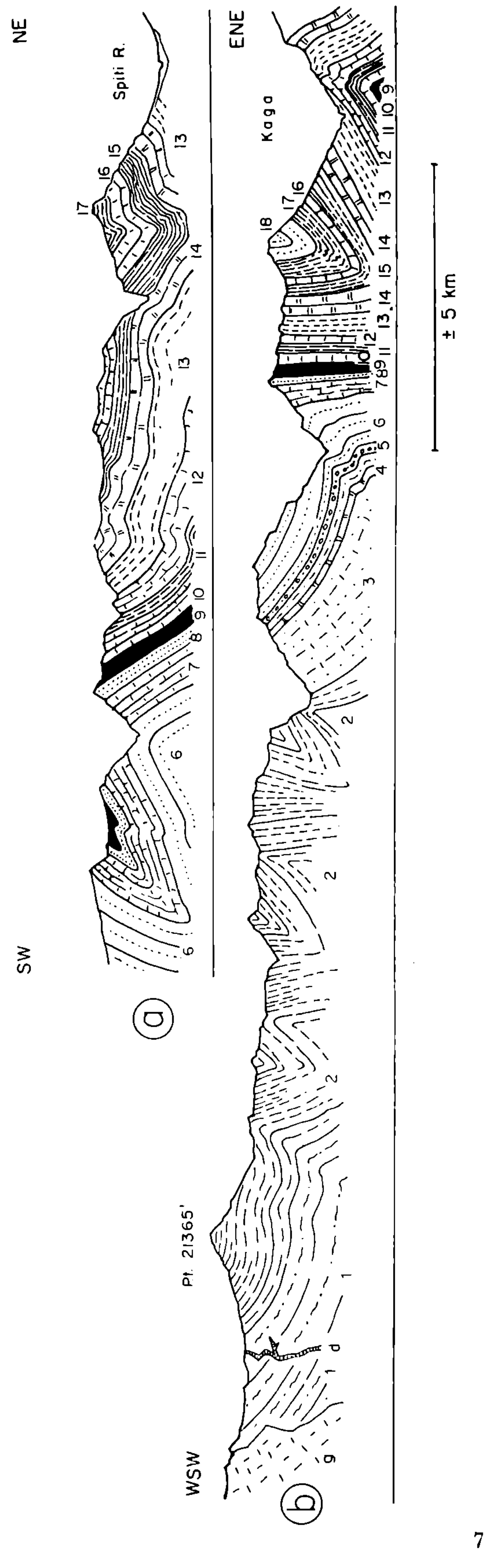
with part of the Dogger forms a comprehensive almost unfossiliferous thick limestone formation (the Kioto limestone) a most conspicuous cliff-forming section, in striking contrast to the soft rolling hills formed by the overlying classical

Fig. 31 *The comformable contact of Muth quartzites with Productus shales.* Head of Teti River, Spiti area; drawn after photo by H. H. Hayden

1 Silurian limestones (forming anticline)
2 Muth quartzites (Silurian-Devonian)
3 *Productus* shales (Permian)
4 Lower Triassic limestones
5 *Muschelkalk*
6 *Daonella* shales

Spiti formation. Together with the Trias it is this section which made the Spiti region world-famous. Spiti ammonites have been sold as amulets since ancient times, and frequently deposited by pilgrims on successfully crossed passes, confusing the geologist by their wrong location. (The writer has found them on granite!) The first and probably still the only large expedition to collect specimens in situ was sponsored by the Geological Survey of India in 1892, with Griessbach, Middlemiss and Diener participating (Diener, 1895). In 1903 and 1910 followed the classical monograph on the Spiti Ammonites of Uhlig. For a concise compilation of the Spiti Jurassic we refer to Arkell (1956).

Lithologically the Spiti shales are characterized by their pitch-black colour and the frequent, often perfectly rounded black concretions which contain most of the well-preserved ammonites.



The shale section is usually less than 200 m thick, but of remarkable constancy in its development. The age of the Spiti section ranges from Upper Oxfordian to Tithonian, but their upper part may actually just straddle the Jurassic Cretaceous border and reach into the Valanginian (Upper Spiti shales).

Conformably covering the Spiti shales and often alternating with their uppermost part follow clastic deposits in the form of yellow-brown sandstones and quartzites—the *Giumal sandstones* (from Giumal in Spiti). The fossils in its basal part indicate a *Lower to Middle Cretaceous age*. The clastics may be the forerunners of the flyschoid deposits widespread in the Upper Cretaceous of the northern Himalayas, in particular the *Indus Flysch*. Upwards the Giumal sandstones change into grey to white limestones with soft grey calcareous shales at the top—the *Chikkim limestones*, named after the Chikkim Hill of Spiti. Fossils are scarce, but the presence of some *Globotruncanae* suggests an *Upper Cretaceous* age. The Chikkim limestones form the stratigraphically highest beds in the Spiti region. It is only farther north, towards the upper Indus River, that the Upper Cretaceous to Eocene Indus Flysch comes in.

Rupshu Granite and the Tso-Morari Gneiss

Between the Spiti area and the Indus in the north we find a highly complicated zone with metamorphics and granites, outcropping in the *Rupshu region*. It was again HAYDEN who in his comprehensive paper on the Spiti region (1904) recognized some relation of the Spiti sediments with the Rupshu metamorphics. He was able

Fig. 32a, b *Geological section along Ratang (a) and Parahio (b) Rivers.* Spiti area; redrawn after H. H. HAYDEN

1 Cambrian slates and quartzites [somewhat altered by intrusion of granite (g)]
2 Cambrian slates
3 Cambrian Trilobite beds
4 Cambrian dolomite
5 Silurian (Ordovician) conglomerates
6 red quartzites
7 Silurian limestones
8 Muth quartzites
9 *Productus* shales
10 Lower Triassic limestones
11 *Daonella* shales
12 *Daonella* limestones
13 grey shales
14 *Tropites* dolomites and limestones
15 *Juvavites* beds
16 Coral limestones
17 *Monotis* shales
18 quartzites (Upper Norian)
g granite

to trace Triassic, Permian and Carboniferous sediments into the slaty and phyllitic rocks on the border of the Tso Morari (Morari Lake) of southern Rupshu.

The Rupshu region is dominated by a *large gneiss dome,* limiting the Spiti basin to the north and separating it from the Indus Flysch further north. Within the Spiti basin we find a tectonic style reminiscent of Jura-type folding, but with sharper and less well-rounded anticlinal structures (Figs. 32 and 40). Northwards, towards the Rupshu crystalline uplift, some of the folds are overturned and steeply southwards-dipping strike faults occur. Along the Tso-Morari a marked north-vergent thrusting has been observed by BERTHELSEN (1951, 1953). The gneiss masses introduce a foreign element into the sedimentary Tethys-type north slope of the northern Himalayas. Cut off in the northwest by the Indus Flysch, the gneisses seem to disappear in a southeastwards direction towards the Tibetan border below Triassic and older sediments. They have not been reported from the wide Pleistocene basin of the upper Sutlej, and except for the Gurla Mandhata gneiss dome no equivalent was observed during the author's traverse to the Kailas Range north of the Kumaon Himalayas (HEIM and GANSSER, 1939). As suggested by BERTHELSEN (1953) the Tso-Morari gneisses may be correlated with the domal gneisses of Gurla Mandhata south of the Raksas and Manasarovar lakes in Tibet.

BERTHELSEN, following HAYDEN, distinguishes a Rupshu granite, forming a sill-like mass 5 km thick with tectonic borders and north-vergent thrusting, and a large dome of the Tso-Morari gneisses (Fig. 33).

The Rupshu granite underlies the already mentioned metamorphic Palaeozoic sediments of the north border of the Spiti basin. BERTHELSEN assumes a tectonic contact with the overlying sediments as well as for the base of this granitic sill, and suggests a tectonic emplacement of the granite. This would explain the discrepancy between the low-grade metamorphism of the surrounding rocks and the high-grade, but partly retrograde metamorphism of the granite. In spite of well-exposed contacts, no veins or dykes from the granite enter the surrounding rocks. Drag folds along the contact suggest the northwards-directed movement of the granite. The amount of thrusting is, however, still doubtful, since even a slight displacement could produce the noted phenomena. It may be questioned whether the observed jump

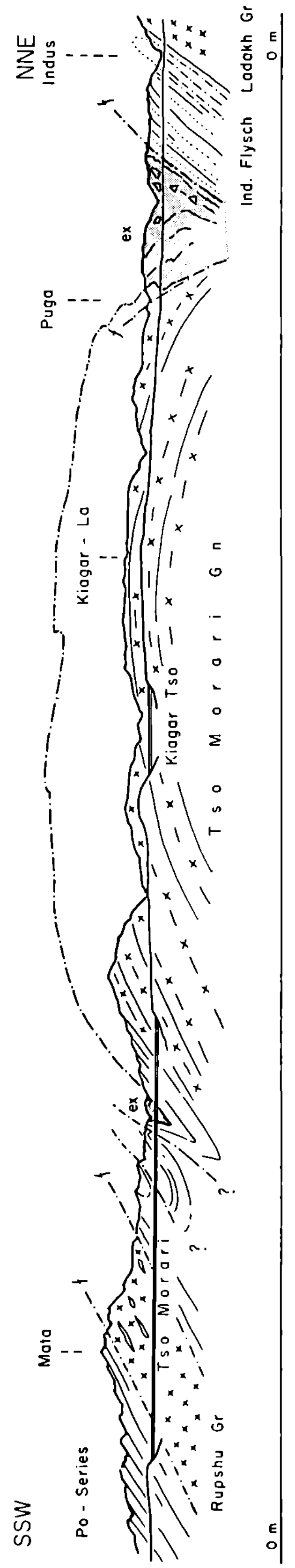


Fig. 33 *Section trough Rupshu granite and Tso Morari gneiss dome;* redrawn and adjusted with new interpretation from A. BERTHELSEN (1957)
ex = ophiolitic Flysch with exotic blocks north of Puga

in metamorphic grade does preclude a granitic intrusion from a deeper granitization level into the low-grade metamorphic surroundings. The retrograde metamorphism (diaphthoresis) of the granite could be subsequent to an intrusive as well as to a tectonic emplacement. The Rupshu granite is a biotite granite with microcline and oligoclase showing reversed zoning. Diaphthoritic granites in the form of flaser gneisses as well as mylonitic forms are present. Strongly boudinaged dolerite dykes occur within the granite.

The Tso-Morari gneiss, following to the north of the sill-like Rupshu granite, covers a large area and forms a somewhat assymetric dome-like uplift with a more clearly developed south flank. Strongly foliated augen gneisses are characteristic, the augen consisting of up to 5 cm large orthoclases. The groundmass contains some microclines, albite, biotite and muscovite. The gneisses were deformed subsequent to the formation of the orthoclase porphyroblasts, and with the deformation went a marked albitization (BERTHELSEN, 1953). The pronounced stratification of the Tso-Morari gneiss must be related to an original bedding, which the granitization process did not destroy. This and the composition of the feldspars distinguishes the Tso-Morari gneiss from the more massive Rupshu granite. The contact with the overlying slates is, according to HAYDEN (1904), gradual. The sediments become garnetiferous, then feldspathic and pass down into the gneiss. Sills of garnet-amphiolite and eclogite occur within the gneisses. Both have been strongly deformed subsequent to their intrusion. Their age, as well as the age of the dolerites within the Rupshu granite, is still a matter of dispute, but the question is important since the age of the intrusive basic rocks may give an upper age-limit for the formation of the granitic rocks. In Spiti and Rupshu, doleritic sills and dykes were observed only in Palaeozoic rocks. Younger basic intrusions and extrusions are found in the more northwards-deposited Indus Flysch. On these admittedly somewhat vague facts one could argue that the dyke system is related to the Upper Palaeozoic (Early Triassic) Panjal type of vulcanism and thus the age of the Rupshu and Tso-Morari granitic rocks may be no younger than Palaeozoic, and probably pre-Upper Carboniferous.

Dras volcanics and the Indus Flysch

The northern part of the Punjab Himalayas is bordered by the upper Indus River basin and is characterized by Upper Cretaceous Flysch-like deposits with basic and ultrabasic rocks, a rare occurence in the Himalayan range (Fig. 34). This Indus zone is the most important tectonic feature of the whole Himalayas, representing, as we will see later, a major suture line and the only section of the whole range where Alpine eugeosynclinal conditions must have existed (GANSSER, 1959). Corresponding rocks in combination with exotic elements will be discussed in the Kumaon section. Unfortunately nothing is known so far of the eastward continuation of this interesting zone.

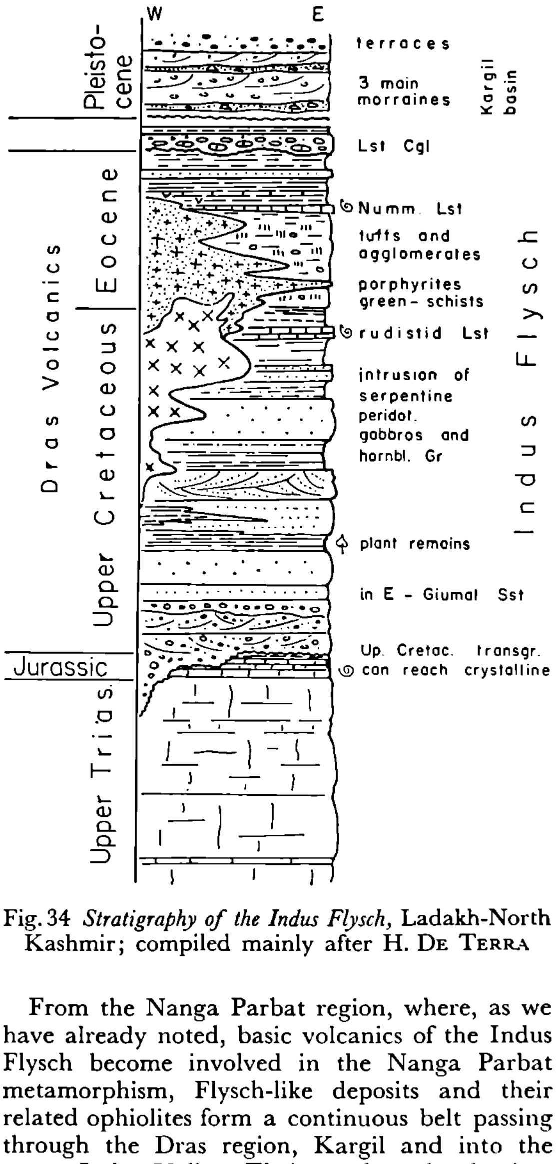


Fig. 34 *Stratigraphy of the Indus Flysch,* Ladakh-North Kashmir; compiled mainly after H. DE TERRA

From the Nanga Parbat region, where, as we have already noted, basic volcanics of the Indus Flysch become involved in the Nanga Parbat metamorphism, Flysch-like deposits and their related ophiolites form a continuous belt passing through the Dras region, Kargil and into the upper Indus Valley. Their southern border is a major tectonic line, with north-directed thrusts (Fig. 35). Along their northern edge, particularly in Ladakh where the large area of the Ladakh granite follows north of the Indus River, a normal transgression of clastic sediments on the granite can be observed.

In the northwestern part, from south of Astor to the Dras region and including the Burzil Pass, the volcanics and pyroclastic sediments have

been called the *Dras Volcanics* (WADIA, 1937). These were previously correlated with the Panjal Traps, with which they have some affinities as far as the coarse pyroclastics are concerned (agglomerates), but their much younger age has been recognized by WADIA on the evidence of associated lenses and blocks of *Orbitolina* limestones. HAYDEN, when traversing this region on his way to Astor, was able to collect some foraminiferal limestones from which DOUVILLÉ (1926) identified *Orbitolina*. This important fact clearly shows that the Dras volcanics are a direct continuation of the Upper Cretaceous ophiolitic Indus themselves cut by an intricate system of dykes and sills of dolerites (Fig. 36). Locally, within the whole complex a special type of breccious to conglomeratic mass occurs, which contains in an unsorted manner practically all contemporary rocks as pebbles or large boulders. WADIA (1937) mentions quartzites, slates, fossiliferous limestones (Cretaceous), tuffs, cherts, hornblende granites and feldspar porphyries. Laterally, these volcanic breccias grade into perfectly homogeneous and well-bedded lava flows. Considering these abnormal breccias as well as the large lenses and boulders of limestones, some with

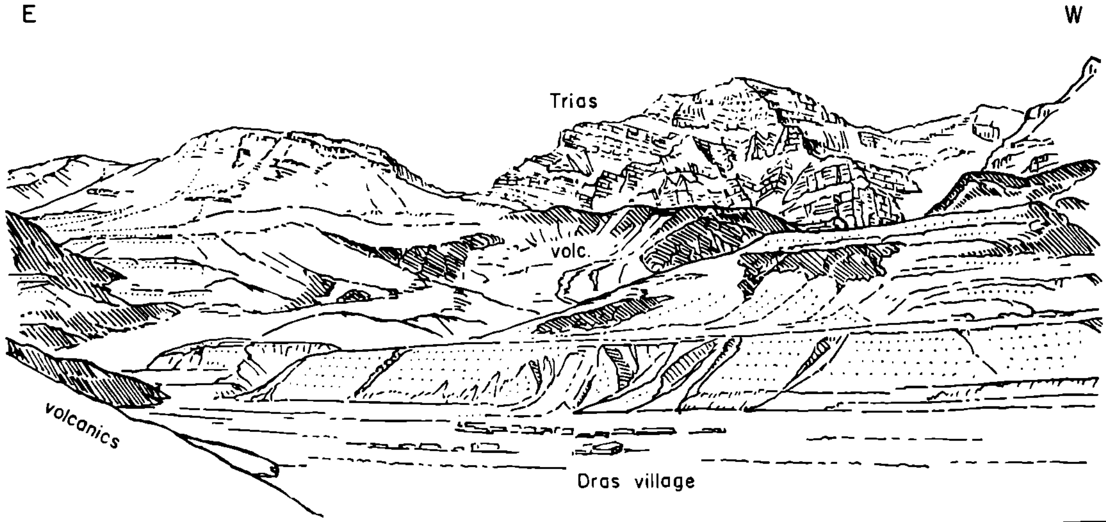


Fig. 35 *The Dras Valley, view towards south, Ladakh;* drawn after photo by H. DE TERRA (1935). Note Triassic limestone thrust northwards over Cretaceous Dras volcanics including ultrabasic rocks. Large Pleistocene gravel terraces with upermost level corresponding to Deosai plateau

Flysch. The Dras volcanics in the widest sense consist of over 2000 m of purple and green laminated siliceous ash beds and tuffs with red cherts or jasper alternating with slates, agglomeratic slates and agglomerates, which grade by an increase in sedimentary constituents to agglomeratic conglomerates. More subordinate are flows of augite andesite to augite basalt. Chloritization and epidotization are common. A considerable amount of the volcanic section, along its southern margin, is formed by stocks, sills and larger masses of dolerites, epidiorites, diallage-gabbros and pyroxenites, the latter more or less altered to serpentines. Somewhat younger than the basic rocks are acid intrusions in the form of large masses of hornblende granite, mostly fine-grained and without any porphyric texture (in contrast to the granites of the Higher Himalayas). Related to these acid intrusions is an intricate network of pink feldspar porphyries. Both granites and porphyries intrude the volcanics and pyroclastic sediments with a most irregular contact, and are orbitolinas and others of a fine crystalline texture and pinkish colour, together with lenses and lumps of ultrabasics, one is reminded of some abnormal deposits which, though most peculiar in their composition, are surprisingly widespread along certain ophiolitic belts which coincide with major tectonic features (GANSSER, 1959). As we will see later in the Kumaon Himalayas, a similarity with the famous exotic block region is apparent.

Structurally, the Dras volcanics display a marked disharmonic folding, with isoclinal structures dipping mostly NNE. Some of the folding must have been syngenetic and some granites intruded into already folded volcanics.

The more eastern extension of the Dras volcanics and their connection with the Indus Flysch has been studied by DE TERRA (1935) in the Kargil basin. The Kargil basin is underlain by granites which belong to the large Ladakh granite body north of the Indus River (Fig. 18). LYDEKKER (1883) observed the transgressive contact of the Indus Flysch on the granites, but sug-

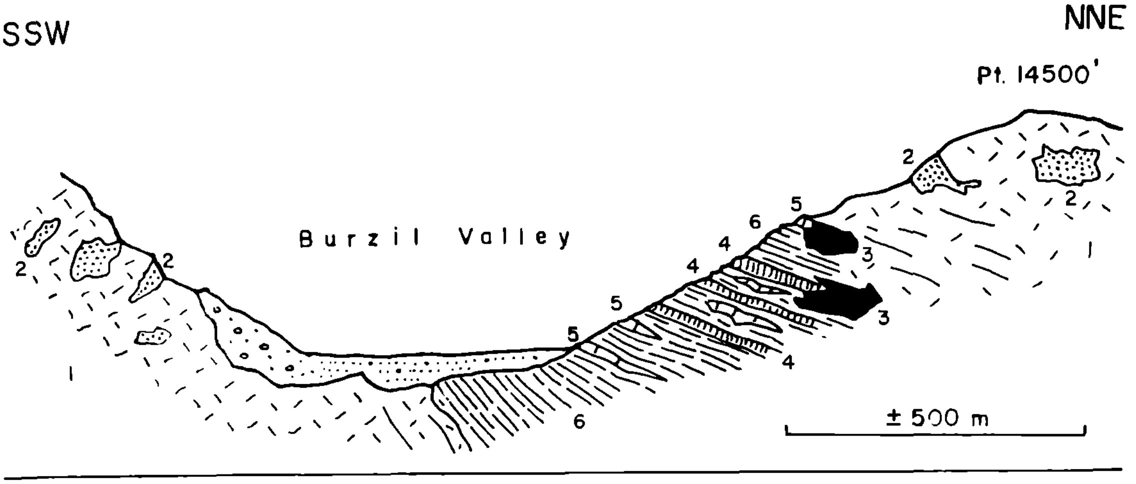


Fig. 36 *Intrusion of fine-grained hornblende granites into highly complex Dras volcanics.* Burzil Valley, Ladakh; redrawn after D. N. WADIA (1937)

1 fine-grained hornblende granite (Eocene?)
2 xenolites of epidiorite
3 serpentine
4 volcanic horizons
5 limestone lenses
6 pyroclastic sediments (Cretaceous)

gested glacial origin for the basal boulder beds. The irregular surface of the granite is covered by a badly sorted assemblage of subangular to rounded pebbles and boulders of granites, diorites, aplites, pegmatites, amphibolites, various basic dyke rocks and vein quartz. The matrix is a red clay. Upwards the conglomerates grade into arkoses and sandstones about 300 m thick. Deltaic bedding is characteristic for this lowest section, and there is a surprisingly great amount of lacerated plant remains. After a section of dark-grey shales there follow more than 2000 m of sandstones locally grading into conglomerates and micaceous shales. Greenish to purplish colours prevail, mainly in the shales. According to DE TERRA (1935) this sandstone section is correlated with the Indus Flysch sensu stricto, which is entirely marine and has yielded a small Senonian gastropod fauna from the base of the thick sandstone body. The relations with the Dras volcanics are not clear, since the latter occur to the south with a thrust contact (Fig. 37). On the other hand, younger beds of Eocene age crop out as purplish micaceous sandstones and shales with intercalations of nummulitic limestones and marls at their base. Of particular interest are the youngest pre-Pleistocene sediments—a peculiar conglomerate outcropping along the Wakka River east of the Kargil Basin. It is composed of Nummulitic and *Alveolina* limestones, Triassic limestones, greenstones, purplish sandstones, shales and quartz. Igneous and metamorphic components are missing (Fig. 38). From all the evidence the transgressive clastics covering the Ladakh granite described by LYDEKKER (1883), are unlike the Indus Flysch from which they are separated by a thrust contact. Together with the post-Lutetian conglomerates they may represent a belt of Tertiary sediments younger then the Indus Flysch and related to the Ladakh Range.

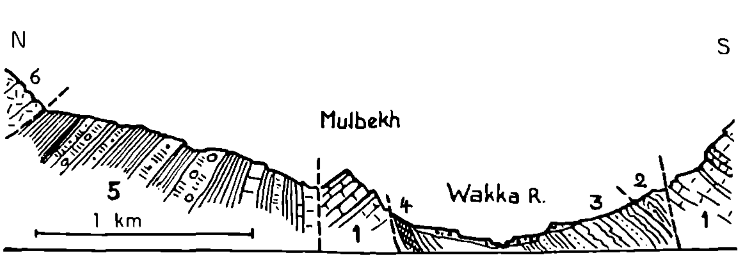


Fig. 37 *The south border of the Dras volcanics* in the Upper Wakka Valley, Ladakh; redrawn after H. DE TERRA (1935)

1 Triassic limestones
2 green schists
3 Flysch sandstones and shales
4 serpentine and chlorite schists
5 agglomerates and shales
6 greenstones

A wealth of information regarding the Indus Flysch and its related basic rocks is hidden in the voluminous work of DAINELLI (1933). He deals also with the Eocene formations of the region of Leh which have furnished Lower to Middle Eocene faunas (Fig. 39).

The recent investigations of BERTHELSEN in the Rupshu area include some information on the Indus Flysch and its basic rocks along the section from Puga to the Indus River (Fig. 33), (BERTHELSEN, 1953), a section already investigated by OLDHAM in 1888. BERTHELSEN recognizes

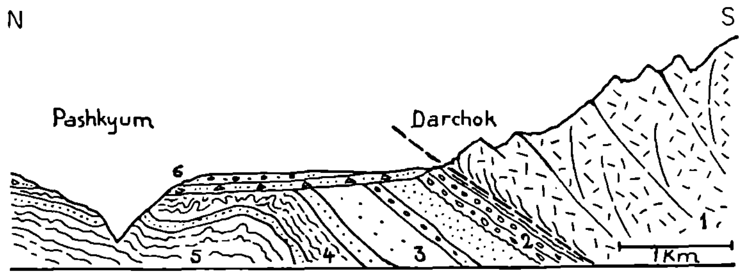


Fig. 38 *North thrust of Dras volcanics on Post Eocene at Pashkyum, Kargil area, Ladakh;* redrawn after H. DE TERRA (1935)

1 Dras volcanics
2 purple limestone conglomerate
3 purple sandstones
4 shales and thin limestones bands
5 green shales
6 gravel terraces

a gradual overturning from north-dipping volcanics with green and red arkosic sandstones and spilitic and noritic intercalations into south-dipping horizons of the main arenaceous Indus Flysch mass. Both contacts, the southern one towards the Tso-Morari gneiss as well as the northern one towards the main Flysch body, are thrusted (Fig. 33). At the turn over from north to south dips huge exotic masses of crystalline limestones are enclosed in an agglomeratic matrix.

It is now interesting to note that just south of the Tso-Morari dome, BERTHELSEN observed phyllites, dark slates and blue crystalline limestones and quartzites together with chromite-bearing serpentines. Their position is not clear, and it is doubtful if their more northern contact with the altered sediments that grade into the Tso-Morari gneiss is normal. One could suggest that the basic rocks with the somewhat abnormal sediments form a remnant of the exotic formation found to the north of the Tso-Morari gneiss, and thus belong to a larger thrust sheet very similar to the thrust exotics in the northern Tibetan part of the Kumaon Himalayas (see next chapter). This interpretation is tentatively indicated on Fig. 33, which is otherwise drawn after BERTHELSEN. With this interpretation it would not be necessary to introduce a second deep ophiolitic suture line such as indicated in the tentative section in BERTHELSEN (1951) (Fig. 40).

The Indus Flysch in the Indus valley shows a very accentuated northern vergence, and this north-directed element is even evident within the Ladakh Range (DE TERRA, 1932). A northwards-overturned anticline is indicated in the Indus Valley, the Indus River cutting into its core (Fig. 33). From all evidence, the tectonics of this north-directed part of the Flysch zone with its counter-thrusts may be much more complicated.

BERTHELSEN (1953) emphasises the major importance and tectonic implications of the Cretaceous ophiolitic belt related to the marine Indus Flysch, which was already realized by DE TERRA (1935). Here, as we have indicated in the Nanga Parbat area, the ophiolitic zone is connected with the most outstanding tectonic element of the Himalayan mountain range (see later).

Fig. 39 *Section between Indus Valley and Skio Valley,* Leh region, Ladakh; redrawn after G. DAINELLI (1933)

1 shales, sandstones and limestones, Middle Eocene
2 siliceous sandstones and shales, Lower Eocene
3 purple sandstones, Basal Eocene
4 green siliceous sandstone, Paleocene?
5 volcanic conglomerate, Paleocene?
6 red and green slates, Senonian
7 Paleozoic, undifferentiated
8 granite

Fig. 40 *Generalized section between Simla and Rupshu;* redrawn after A. BERTHELSEN (1951)

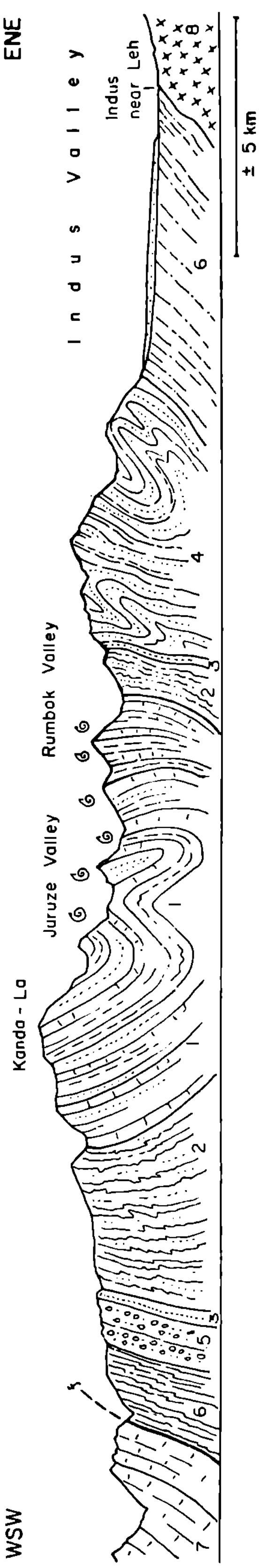

WSW
ENE
Kanda - La
Juruze Valley
Rumbok Valley
Indus Valley
Indus near Leh
± 5 km
1
2
3
4
5
6
7
8

Fig. 39

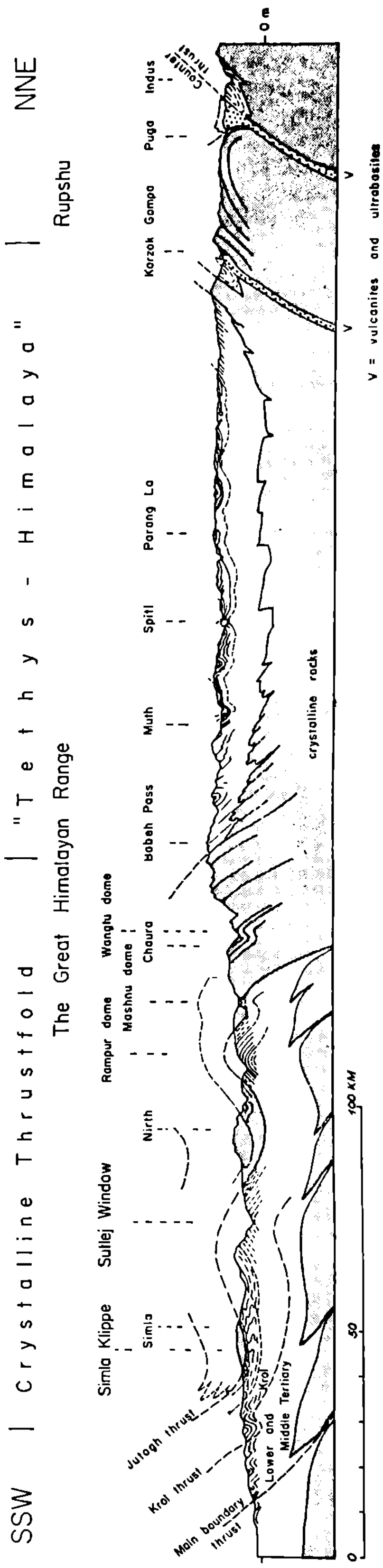

SSW
NNE
Crystalline Thrustfold
"Tethys - Himalaya"
Rupshu
The Great Himalayan Range
Simla Klippe
Sutlej Window
Simla
Nirth
Rampur dome
Mashnu dome
Choura
Wangtu dome
Bobeh Pass
Muth
Spiti
Parang La
Korzok Gompa
Puga
Indus
Counter thrust
Jutogh thrust
Krol thrust
Main boundary thrust
Krol
Lower and Middle Tertiary
crystalline rocks
V = vulcanites and ultrabasites
0 m
0
50
100 KM

Fig. 40

CHAPTER VI

KUMAON HIMALAYAS

The Kumaon Himalayas include the 320 km stretch of mountains which lie between the Sutlej in the west and the Kali River at the western border of Nepal in the east. As in the Punjab Himalayas much pioneer work was done at the turn of the century, and was followed by more modern investigations between 1930 and 1940. Stratigraphically and structurally, the Kumaon Himalayas are a direct continuation of the eastern Punjab Himalayas, except that tectonic complications are more severe in the Lower, Higher, and Tibetan Himalayas, without however, destroying the excellent faunal evidence of the latter region.

In the Kumaon Himalayas we include the problematic zone of the *exotic blocks*, as well as the stretch towards and including the Trans-Himalayan range with the famous *Kailas mountain*, studied by the writer in 1936. In spite of the considerable amount of work done already in the Kumaon Himalayas, this stretch of mountains is still dotted with unsolved problems and remains, in my opinion, one of the most inspiring places of geology of our globe. It is only regrettable that one of the most problematic parts, the region of southern Tibet, is for the time being closed to geological investigations.

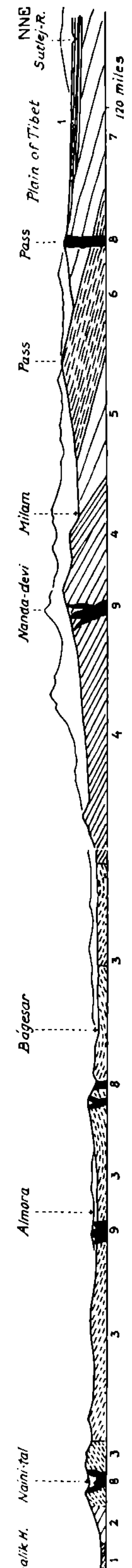
In 1851 CAPTAIN STRACHEY published his results on the Central Himalayas (as the Kumaon section is generally called) and produced the first maps and sections. His cross section through our present zone of interest reflects the main subdivisions surprisingly well. He recognized the Palaeozoic and Mesozoic beds of the Tibetan Himalayas (Fig. 41a). A similar section published in the revised edition of the *Geology of the Himalaya* by BURRARD and HAYDEN (1934) over eighty years later shows no progress at all and its interpretation hardly reaches the level of STRACHEY (Fig. 41b). On the other hand, in the same volume, there is much valuable new information based on the up to date research prior to the revision.

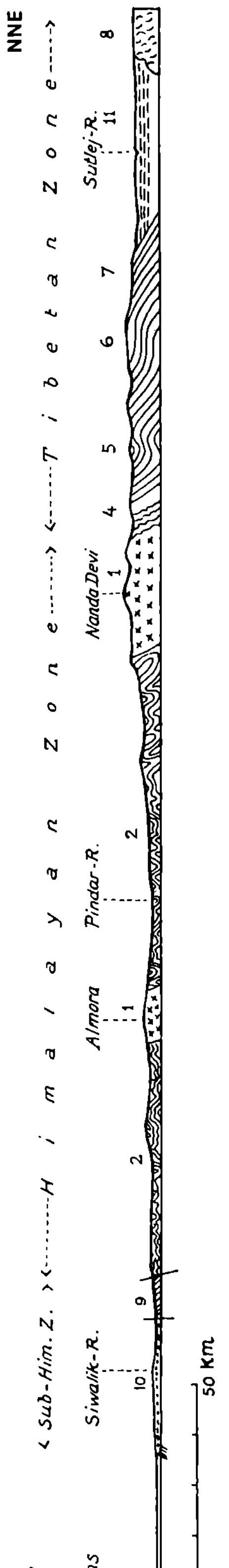
A new phase of geological work began with the brilliant investigations of AUDEN, beginning in the Krol belt southwest of the Sutlej (1934) and his subsequent mapping of the foothills and traverses into the interior (1935, 1937). AUDEN was the first to recognize the magnitude of the crystalline thrust sheets of the Kumaon Himalayas and his findings were fully confirmed by the work of HEIM and GANSSER (1939) when the present author extended his investigations into the Tibetan Transhimalayas.

The four-fold division of the Kumaon Himalayas into Sub-Himalayas, Lower Himalayas, Higher Himalayas and Tibetan Himalayas is here even better applicable than in the Punjab Himalayas, and the various sections are somewhat clearer defined. When discussing the Tibetan Himalayas special emphasis will be given to the problem of the exotic block regions, and to the area lying between the northern Himalayas and the Transhimalayas or the Kailas Range, since it is an area where, after the investigations by HEIM and GANSSER, practically no new work has been carried out and no such work seems to be possible in the near future. A few of the major problems can be interpreted with some new ideas, and it was particularly the recent work of the author in the Middle East which led to some interpretation differing from the one presented in the 1939 publication of the Central Himalayas (GANSSER, 1959).

SUB-HIMALAYAS OF KUMAON

Here, as everywhere else along the Himalayan chain, only Tertiary deposits are involved in the foothill belt. Contrasting, however, with the wide Tertiary belts of the Punjab Sub-Himalayas, the foothills of Kumaon are narrower, and most of the Lower Miocene Murree-type sediments have disappeared. The change is relatively abrupt southeast of the Sutlej River, and coincides with a marked southwards bulge of the Lower Himalayas characterized by the Krol thrusts (south of Simla, see map Pl. I). From the Krol region to the southeast, all along the remaining Hima-





layan range, the foothill belt is built entirely of Siwalik sediments. Eocene beds are involved in the Lower Himalayas and are thrusted over the Siwaliks. They will be discussed in the next section.

The Siwaliks of the Kumaon Sub-Himalayas can generally be subdivided into a Lower, Middle and Upper part, but it is not certain if this threefold division really corresponds to the Lower, Middle and Upper Siwaliks of the Punjab Sub-Himalayas. In the western part of the Kumaon Sub-Himalayas, near the Sutlej River, the lower part is called *Nahans* (Simla area) and follows without a sharp break over the *Kasaulis*, which are the equivalent of the uppermost Murrees. The Nahans or Lower Siwaliks are very widespread along the Kumaon foothills, and newer investigations have shown that only relatively small remnants of Middle to Upper Siwaliks are actually present. The Nahans show an alternation of massive, soft green-brown sandstones with chocolate to green, somewhat concretionary clays. A coarse current bedding is found in the sandstones, and together with the clays, they are often streaked with purple, lending a purplish aspect to the whole formation and distinguishing it from the overlying Middle and Upper Siwaliks. The carbonate content of the sandstones can locally be rather high. Typical here are microscopic fragments of volcanic rocks, seen as chloritized glassy andesite and basalt components (AUDEN, 1934).

In the eastern foothills the *Lower Siwaliks* are well exposed along the Katgodam-Naini Tal road. They consist of variegated (violet, red and green) clays, often concretionary and nodulous and thick to well-bedded, partly calcareous sandstones. Here the Siwaliks show abnormal cross structures and it seems that the Lower Himalayan thrust

Fig.41a *The "first" geological section across the Kumaon Himalayas;* redrawn after R. STRACHEY (1851)

1 Tertiary
2 Secondary or Paleozoic?
3 metamorphic strata without fossils
4 crystalline schists
5 azoic slates
6 Paleozoic
7 secondary
8 greenstones
9 granites

Fig.41b *Diagrammatic section across the Kumaon Himalayas;* redrawn after BURRARD and HERON (1934)

1 granite
2 Purana group
3 Vaikrita system (not in this section)
4 Haimanta system
5 Muth and Kuling system
6 Lilang system
7 Cretaceous and Eocene
8 Ngari Khorsum volcanics
9 Lower Siwalik
10 Upper Siwalik
11 Pleistocene of Ngari Khorsum

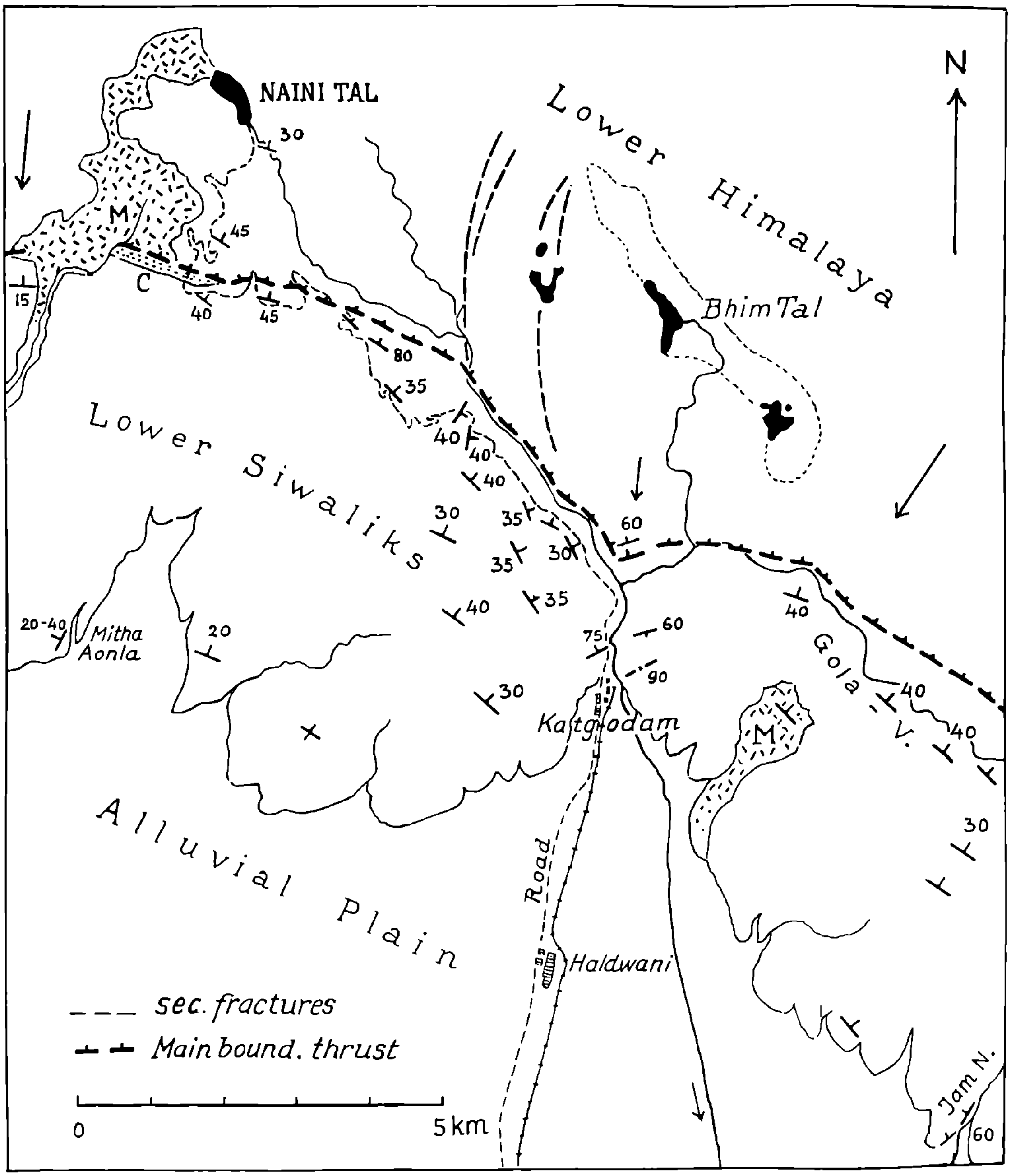


Fig. 42 *Structural sketch map of the Katgodam-Naini Tal region;* after HEIM and GANSSER (1939) with additions by A. N. THOMAS (1952)

is over-riding a structural and erosional gap in the Siwaliks (relief thrusting) (Fig. 42). In the easternmost part of the Kumaon foothills, just bordering the Kali River at the Nepalese frontier, MISRA and VALDIYA (1961 a) made a detailed sedimentary and petrological study of the Siwaliks. In this *Tanakpur area* the 8 km wide foothill belt consists of normal sections of northwards-dipping beds without repetitions, inversions or imbrications. Locally, longitudinal faulting is responsible for a sudden change in dip, without, however, cutting out much of the section. In line with most of the normal sections along the Kumaon foothills, Lower Siwaliks form the predominant outcrops, and have been divided into a lower, middle and upper part (Fig. 43).

The lowest, southernmost outcrops consist of soft and friable brownish grey to purplish fine-grained sandstones, frequently mottled with red. Muscovite is generally present. The sandstones alternate with brick-red siltstone and clayey shales. They are overlain by medium-grained calcareous sandstones of the middle part which are massive, with a conspicuous "salt and pepper" appearance. Contrasting with the muscovite content of the lower part, biotite is frequent in this middle part and may indicate some pyroclastic influence. Intercalated, though rather subordinate, occur brown to grey shales. Along the Kali River well-preserved carbonized leaves were found in these shales, together with local pockets of coal. Upwards the sandstones become coarse with inclusions of yellow and brown clay pellets. In Siwalik sections, such clay pellet inclusions have been generally called intraformational conglomerates, not quite an appropriate term. These clay pellet sandstones can grade into thin-bedded real conglomerates with white, pink and grey quartzite pebbles, oriented within the stratification plane. The highest outcrops of the Siwaliks consist again of fine-grained but compact and hard, grey-brown to greenish sandstones with subordinate purple clay intercalations. They are generally very poor in micas and resemble somewhat the lower section.

Towards the thrust zone of the Lower Himalayas (the Main Boundary Fault) the sandstones become somewhat quartzitic. They are otherwise not tectonized, although the old quartzites and green schists of the Lower Himalayas are highly sheared and mylonitized along the thrust. The dips within the Siwaliks are rather constant, with 50° to 70° towards north or northeast at the Kali River. They strike here in a southeast direction into the wide arch of the Siwaliks of westernmost Nepal.

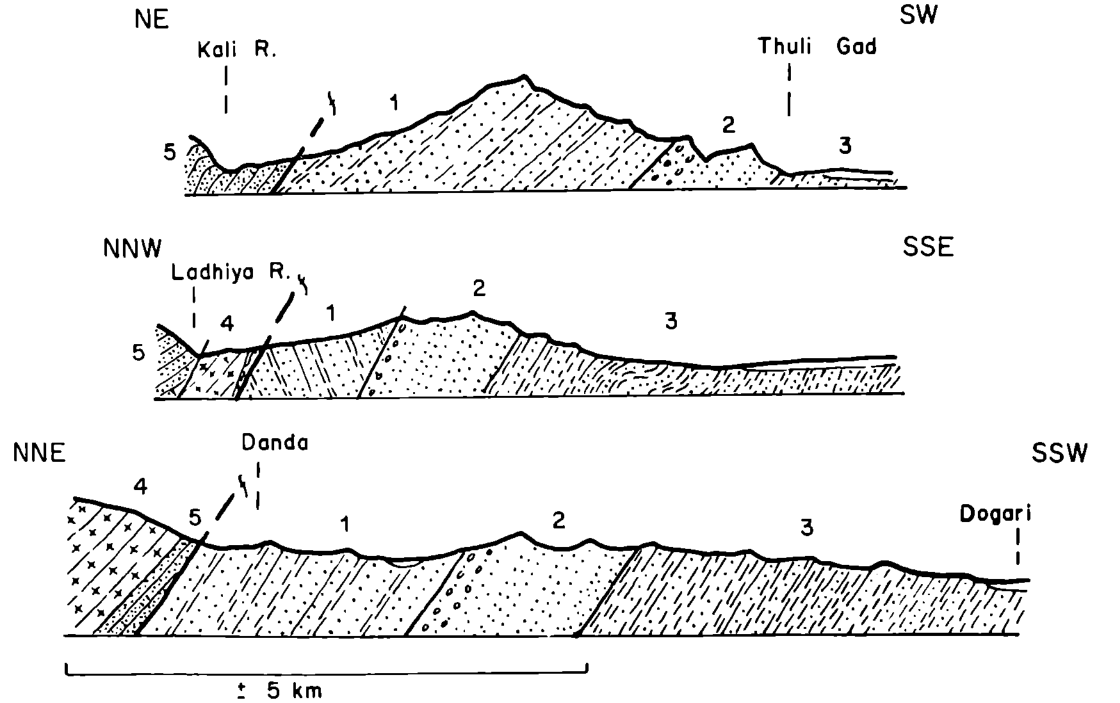


Fig. 43 *Section across the Siwaliks of the Tanakpur area,* southeastern Kumaon; redrawn after R. C. MISRA and K. S. VALDIYA (1961)

1 upper zone, 2 middle zone, 3 lower zone } Lower Siwaliks
4 trap
5 quartzites
ſ Main Boundary Fault

Based on grain-size analysis and detailed petrological investigations, MISRA and VALDIYA assume a rhythmical sedimentation for the lower section, with a high proportion of fine material. The sands consist chiefly of quartz grains (over 50%), mostly subangular. A relatively high percentage of slate and phyllitic fragments (10%) indicate a sub-greywacke type of sandstone. Micas are frequent, except in the upper sandstones. The heavy mineral content is rather similar in the three sections, with only local variations. Garnets and tourmalines are predominant, followed in

abundance by zircons and kyanite. Less frequent are epidote, apatite, rutile and sphene. The garnets often show etching; a pinkish type without inclusions is abundant, while less frequent are colourless garnets rich in inclusions arranged in the centre. These latter resemble some garnets from the mesograde metamorphics of the main crystalline thrust in the Kali Gorge. Two types of zircons exist; the generally distributed larger grains which are very well rounded and have a frosted surface may be the product of several cycles of erosion and deposition. Zircons of a prismatic and bipyramidal habit, somewhat smaller in size, occur in some layers.

The predominantly red colour of the lower section suggests tropical conditions during the sedimentation. Much of the grey colour in the shales is due to reduction by the frequent plant debris. Based on the mineral content, most of the detrital sediments have been derived from igneous rocks (subangular quartzes without strain) in the lower section and metamorphics in the middle and upper sections. The association of sub-greywacke sandstones and red siltstones and shales (clays) is very persistant over wide areas, as we have seen already in the Punjab foothills. The rather constant lithology and the rhythmic sedimentation do not suggest deltaic origin for the sediments of the Lower Siwaliks, but rather red-bed-type deposits in a basin subsiding with the sedimentation. Whether the rhythmic sedimentation was caused by the introduction of sands by turbidity currents, or whether the change was a reflection of high and low velocity sedimentation caused by a monsoon-type climate, remains an open question. I feel that turbidites may not be the explanation in such a shallow basin, but rather that changes in water velocity during secular dry and wet periods were responsible for the rhythmic sedimentation, and not variations during a monsoon cycle as the repetitions seem too coarse.

Deltaic sedimentation began with the Upper Siwaliks after an intermediate stage in the Middle Siwaliks which reflected a sedimentation in channels, parallel to the rising mountain front, such as envisaged for the already discussed Indo-Brahm of Pascoe (1919).

The Middle and Upper Siwaliks of the Kumaon Sub-Himalayas are preserved just east of the

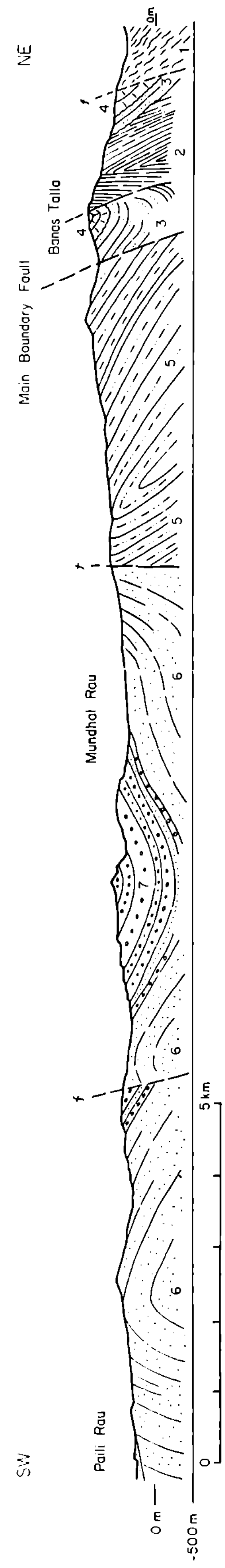


Fig. 44 *Section across the Siwalik foothills east of the Ganges River;* after C. S. Middlemiss (1887)

1 metamorphics
2 purple slates
3 Tal quartzites
4 nummulitic
5 Nahan, Lower Siwaliks
6 Middle Siwalik sandstones
7 Upper Siwalik conglomerates

Sutlej, west and east of the Ganges River and between the Ganges and the foothills of Naini Tal, where they were investigated by MIDDLEMISS (1887, 1890). The contacts between Middle, Upper and Lower Siwaliks are frequently faulted along strike faults, reminiscent of the very long strike faults paralleling the foothills of the Punjab Himalayas (Fig. 44).

The lithological composition of the *Middle Siwaliks* does not differ from the section already discussed (Punjab Himalayas). Thick, massive, rather soft micaceous sandstones with subordinate clays (shales), distinguished from the Lower Siwaliks by their less vivid colours, form the main deposits. Large irregular sandstone concretions with calcareous cement, where fossils are often preserved, are frequent.

In the *Upper Siwaliks* the dominant rocks are coarse clastic deposits, such as boulder conglomerates, ordinary conglomerates, grits, sands and earthy clays. The deltaic influence of the Himalayas is felt, but still not so accentuated as for instance in the Alpine Molasse with its well-outlined local river fans. Channeling along the foothills is still important, and the configuration of the environments was probably not very much different from that seen along the present foothills, with the elongated depressions (the Duns) diverting the large Himalayan rivers from considerable transverse stretches into courses parallel to the foothills.

One point of importance emerging from older as well as recent studies of the Siwalik ranges is the fact that in spite of strong faulting, some folding and steep thrusting, *the Siwalik sections are practically everywhere normal.* This fact was not always generally accepted, and large reversed sections were assumed for the Siwaliks by some authors (MEDLICOTT, 1876, DYRENFURTH, 1931, WAGER, 1934). Such normal sections are even more relevant when we recognize how large tracts of the Lower Himalayas (Sikkim) are thrust in a reversed position over the Siwaliks. The normal position of the Siwaliks clearly shows the large structural discrepancy between Siwaliks and thrusted Lower Himalayas, and indicates that *the Siwaliks are not the normal cover of the Lower Himalayas* (HEIM and GANSSER, 1939).

LOWER HIMALAYAS OF KUMAON

The intricate geology of the Lower Kumaon Himalayas was unraveled only after some clarity had been obtained of its complicated tectonics. The almost complete absence of fossils in the Lower Himalayas on the other hand leaves many stratigraphical problems unsolved, since up to now correlation had to be based on lithology only. This drawback in return casts some doubts on certain tectonic interpretations on which, closing the "viscious circle", the adopted stratigraphical sequence so far depends. It is with these difficulties in mind, that the geology of the Lower Kumaon Himalayas has to be approached.

Much progress has been made in the Lower Himalayas since the excellent investigations of AUDEN (1934, 1937) who built on the previous surveys by PILGRIM and WEST (1928) and older workers. For the Simla region and the southern Lower Himalayas there are now good quarter inch geological maps, prepared systematically by the Geological Survey of India—a mapping campaign which unfortunately has not progressed much in later years. The eastern and inner part of the Lower Himalayas was investigated by HEIM and GANSSER (1939) and recently some more local studies covered the southeastern part (NAUTIYAL, 1953; MISRA and VALDIYA, 1961 b; VALDIYA, 1962 b).

In the Kumaon Lower Himalayas we can distinguish the *Krol belt*, stretching from the Simla region in the northwest to Naini Tal in the southeast, and an inner sedimentary belt, the *Deoban-Tejam zone*, separated from the outer zone by crystalline thrust sheets of which the *Almora-Dudatoli crystalline mass* is by far the largest. We will first discuss the Simla Krol belt, then the Deoban-Tejam zone and lastly the Almora-Dudatoli crystalline thrust sheet.

Simla Krol belt

For the Simla Krol belt we refer to the papers by AUDEN (1934), PILGRIM and WEST (1928), and WEST (1931, 1939) on which our following interpretation is mainly based. A tentative stratigraphical column helps to distinguish the various formations (Fig. 45).

The oldest and most characteristic rocks of the Simla Krol belt are the *Simla slates*. They have already been correlated with the Dogra slates of the Punjab Himalayas. Characteristic are: dark sombre bluish-grey slates; clay slates, and, when cleaved, pencil slates; micaceous shales, and some sandstones, predominantly greywackes. Bedding varies from a few centimetres to 3 m, but the general aspect is massive. Locally quartzitic concretions, quartzites with current bedding and ripple marks and green micaceous silts are met. Furthermore a characteristic limestone is intercalated, the *Kakarhatti limestone*, which is microcrystalline and oolitic with irregular cherty patches and layers. The oolites give the limestone a pseudo-organic appearance. Some of the cherty zones show *Collenia*-type growths and have been correlated with newly discovered stromatolitic structures from the Shali limestone near Simla and from the calc-zone of Pithoragarh

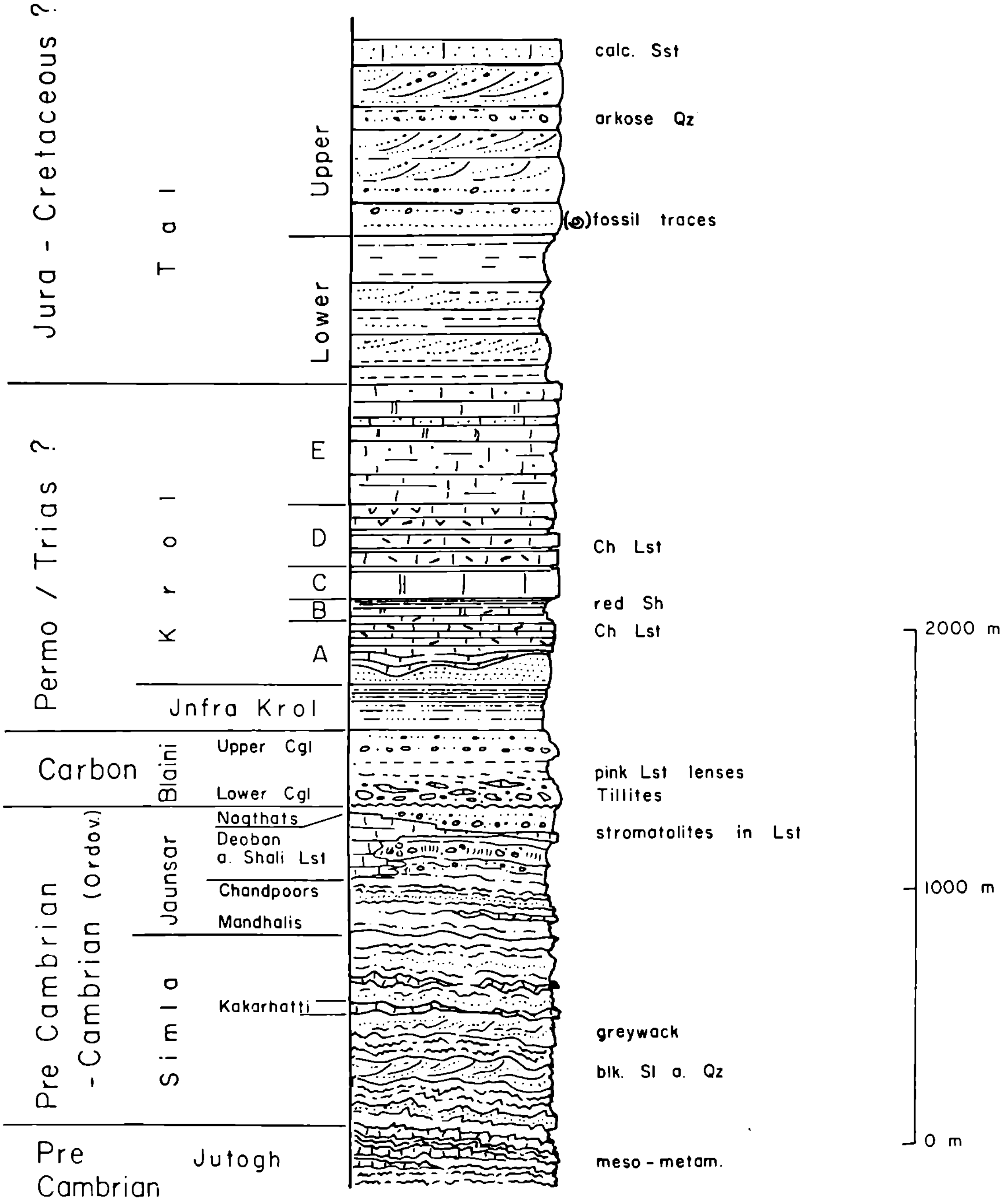


Fig.45 *Stratigraphy of the Simla-Krol belt;* compiled mainly after J. B. AUDEN (1934) and W. D. WEST (1939)

in SE Kumaon (MISRA and VALDIYA, 1961 b, 1962).

In the Simla area we find metamorphosed rocks overthrust on the Simla slates. Some are very similar to the Simla slates, but others, like the *Jutoghs*, named after a place near Simla, are regarded by some authors as the oldest rocks in the Kumaon Himalayas (PILGRIM and WEST, 1928). Since normal contacts are tectonically obscured, it is questionable whether the Jutoghs are a metamorphic equivalent of somewhat younger rocks, or if we actually have an older sequence which would normally be covered by the Simla slates. Based on the somewhat different lithology of the Jutoghs as compared to the Simla slates the latter suggestion seems more likely. The Jutogh consist of black carbonaceous garnetiferous phyllites and slates, quartzites and mostly

highly crushed dolomites. Intercalated are hornblende schists and hornblende gneisses. In our stratigraphical section (Fig. 45) the Jutoghs have been regarded as the oldest rocks, and in this case should be correlated with the *Salkhalas* of Kashmir.

This difficulty in stratigraphic correlation in the Lower Kumaon Himalayas is due to the fact that the true Simla slates are autochthonous or parautochthonous, and most of the younger or older formations have tectonic contacts. As autochthonous formations, the Simla slates represent a border facies of the Peninsular shield rocks, most likely as a steeply folded continuation of the Aravalli trend. It is significant that autochthonous rocks such as the Simla slates are restricted to the Kumaon Himalayas in an area where the continuation of the Aravalli Range should be expected (see tectonic map, Pl. I B).

The normal cover of the autochthonous Simla slates, preserved locally below the various thrusts, are *Eocene deposits*, which, though highly tectonized, are still in a normal stratigraphical relation with the Simla slates (Fig. 47). The enormous stratigraphical gap from Precambrian to Eocene is remarkable, but seems a widespread fact in the more or less autochthonous belt of the Kumaon Lower Himalayas and Sub-Himalayas as well as in the eastern Salt Range (Fig. 5) (refer also to the Eocene on Jammu limestones in Punjab). The Eocene rocks are refered to as Subathus, from a place near Simla, and consist of calcite-veined olive shales, green and white sandstones and ferruginous quartzites and calcite-veined shelly limestones with some nummulites. The shells are mostly broken oysters and, based on the nummulites, the age is Middle to Upper Lutetian.

Following above the dislocated Simla slates, though with some obscured contact relations, AUDEN describes the *Jaunsars*, which are complex and still most problematic deposits. Their separation from younger formations with which they have been paralleled by some authors (PILGRIM and WEST, 1928), has been proposed by AUDEN as a result of his detailed work in the Krol belt. Even AUDEN is, however, not certain whether the lower part, called the *Mandhalis* and characterized by conspicuous boulder beds should be fully separated, or if a possible correlation with the younger Blaini boulder beds is after all still a possibility.

The generally adopted sequence of the Jaunsars is, from bottom to top, the *Mandhalis*, the *Chandpurs* and the *Nagthats*.

The *Mandhalis* begin with quartzites and shales and are followed by crystalline limestones or marbles. They are banded by intercalations of slates or phyllites. Gritty to conglomeratic quartzites pass into the conspicuous *Mandhali boulder beds* which merit a more detailed investigation, since they have been compared to the tillitic Blaini boulder beds. In a slaty or gritty to sandy matrix occur boulders and pebbles of dark microcrystalline or white marmorized limestones, dark slates, sheared quartzites and vein quartz; metamorphic or igneous rocks are missing. The distinct boulder beds, which may grade into conglomerates, probably occur at different horizons. Thin intercalated elongate sandstone and limestone bodies seem to form an integral part of the sequence. The Mandhalis are invariably overlain by dark microcrystalline limestones with interbedded pyritic slates. Just at the base of these limestones and in contact with the boulder beds thin graphitic schists are intercalated. The topmost limestones of the Mandhalis are typically dark blue-black with conspicuous sand grains and with a much coarser bedding than the deeper calcareous horizons.

The *Chandpurs* which follow above the Mandhalis, though mostly separated from these by thrusts, are characterized by a most conspicuous banding of fine quartzites and phyllites, with up to a dozen of such bands per centimetre. Strikingly crinkled folds are frequent. Thicker quartzites follow, together with green chloritic tuffs and tuffaceous slates. The pyroclastic nature is evident in the upper horizons, and even the fine banding in the lower beds may be partly due to tuffaceous influence.

The *Nagthats* are less well-defined, with sandstones, arkoses, grits, quartzites, conglomerates and purple and green clay slates and phyllites. Locally boulder beds were observed, with slates, phyllites and quartzites but no limestones, which distinguishes them from the Mandhali boulder beds.

Somewhat similar to the complex Jaunsars are the rock sequences outcropping in the tectonic *Shali window* along the Sutlej River north of Simla (Fig. 46). The Shali section, mapped by WEST (1939), consists of quartzites at the base followed by the lower Shali limestones in which stromatolitic structures have recently been observed (VALDIYA, 1962a). After some slates and slaty limestones one passes into the upper Shali limestones, topped by pure white quartzites with cherts, the Shali quartzites. Locally some *Eocene Subathu* sediments are preserved, transgressive on the Shali rocks and overthrust by semi-metamorphic equivalents of the Jutoghs or a different type of Simla slates.

PILGRIM and WEST (1928) place the Shali section somewhere between the Simla slates and the Blaini conglomerates. Later, WEST (1939) correlated the Shali sequence with the younger Krols. The presence of stromatolitic structures and the type of the massive dolomitic limestones with the typical chert bands, so characteristic

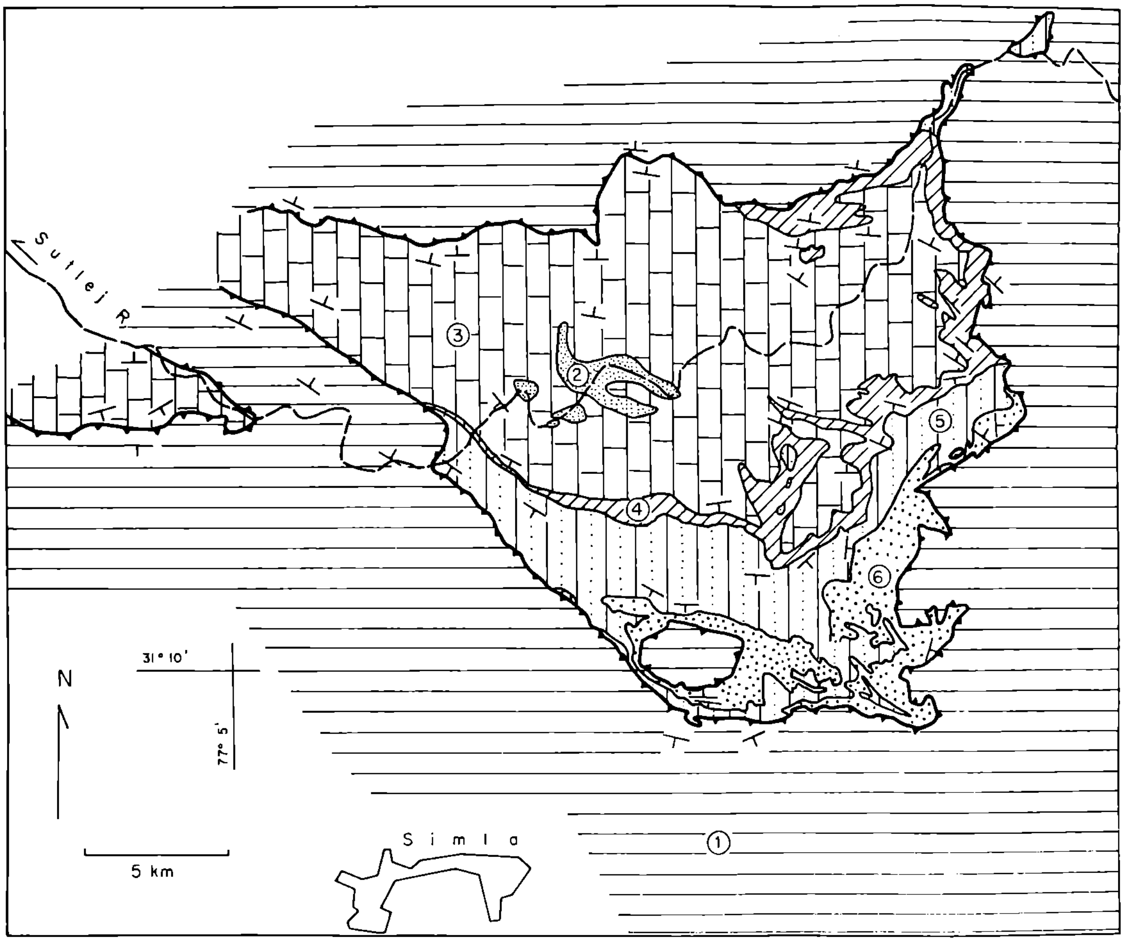


Fig. 46 *Geological map of the Shali Window.* Simla area, Kumaon Himalayas; redrawn after W. D. WEST (1939)

1 Simla slates and Jutoghs
2 Khaira quartzites
3 Lower Shali limestones
4 Shali slates
5 Upper shali limestones and quartzites
6 Madhan slates and Tertiary (Subathu)

for the late Precambrian-Cambrian dolomite-limestone formations of the Middle East rather suggest a correlation of the Shali sequence with a more northern Simla facies and with the Deoban limestones sections to be discussed in conjunction with the Inner Sedimentary Belt.

Following upon the Jaunsars are the *Blaini boulder beds*. They seem to transgress onto various older formations, but here too, the relations are far from clear. The Blaini boulder beds have been correlated with the *Talchir boulder beds*, and their tillitic aspect seems rather undisputed. If this correlation is correct they form one of the most important stratigraphical markers in this surprisingly unfossiliferous and lithologically complicated sequence of the Lower Himalayas. But just for this reason it is most important to distinguish the Blaini boulder beds from the older previously mentioned boulder beds, which, considering the tectonic complications and the often scattered outcrops, is often very difficult. By no means all the boulder beds of the Himalayas are glacial tillites and evidently all are not Blainis.

The Blainis consist of two typical rock types; one is the boulder bed, the other the limestones, overlying the former. This striking rock association is, however, not at all constant, and often the boulder beds can occur alone, or only limestones are met, or even several horizons of boulder beds are found together with the limestones, though these complications may be caused by tectonic imbrication.

The boulder beds are generally dark grey-brown to greenish. In a matrix of hard clay or quartzitic grits one observes badly sorted boulders ranging from 1 m to very small pebbles. The matrix shows ungraded fragments of quartz in a dirty, fine-grained quartz clay mass. Secondary sericite is frequent, increasing in size in the more tectonized parts of the boulder bed. Exceptionally,

the matrix can be dolomitic or is made up of fine calcite. The pebbles are angular to rounded and consist of dark slates, greenish quartzites, pale quartzites, grey sandstones, green siltstones, banded slates, vein quartz and occasionally microcrystalline limestones. Except for the limestones, the provenance of boulders and pebbles is local, derived from Simla slates and Jaunsars, while the origin of the limestones is uncertain. Here again, as in all older boulder beds, metamorphic and igneous rocks are missing. Striated boulders do occur, and the author has collected some striated pebbles from the Blainis northwest of the Ganges River while visiting AUDEN in the field in 1936. The tillitic aspect of the Blainis is generally accepted and its correlation with the Upper Carboniferous Talchir boulder beds with their Gondwana flora seems to make sense. We should, however, not forget that we are in an unfossiliferous section, highly complicated by intense thrusting, where various boulder beds do occur, and which certainly do not all have a glacial origin. Striated pebbles and boulders can be found in mud flows and even in some fanglomeratic deposits and are therefore not all convincing proof for a glacial provenance. Mud flows and fanglomerates would, however, hardly occur at such a constant level as is occupied by the Blainis, which are invariably followed by the whole sequence of Krol rocks, a fact which distinguishes them clearly from the much more erratic older boulder beds.

The Blaini limestones are characteristically pink and microcrystalline and probably dolomitic and siliceous, since they do not react with acid nor do they scratch with a knife (AUDEN, 1934). Upwards, they become increasingly argillaceous and grade into pink or purple calcareous shales and slates.

The overlying deposits of the *Krol belt*, named after the Krol mountain in the Simla area, have been subdivided into Infra Krol, Krol sandstones, Krol limestones and the Tal quartzites (Fig. 45). In spite of tectonic complications, the various formations of the Krol belt can be well distinguished and AUDEN's masterful account of the Krol belt gives all the pertinent information (AUDEN, 1934).

The Blaini boulder beds and overlying limestones grade imperceptibily into a very incompetent section of dark shales, slates and banded quartzites ending in conspicuous black carbonaceous shales or slates. Some of the finer banded shales and quartzites show a varved aspect. Intense folding and faulting have affected this section, which is also subject to various grades of slight metamorphism, altering some of the shales into slates and even silvery phyllites, often strongly quartz veined. A clear distinction from older Jaunsars is thus not always easy, but the position between Blainis and the overlying Krol sandstones leaves little doubt as to the proper location of these beds, which accordingly have been called *Infra Krols.*

With a rather sharp contact the Infra Krol sequence is overlain by the *Krol sandstones*, a badly bedded, orange-stained horizon. The sandstones often contain shale fragments, only a few millimetres thick and 5 cm long, which are probably derived from the underlying Infra Krol. The smaller quartz grains (0.10 mm) of the sandstones are mostly angular, while the larger grains (0.30 mm) show a perfect rounding. Some of the sand is probably of aeolian origin. The Krol sandstone is not always a single horizon, but can split up locally into sand beds with intercalated shaly sections.

Above the sandstones follows the main unit of the Krol belt, consisting of 600-1500 m thick limestones and calcareous shales, generally known as *Krol limestones.* AUDEN has subdivided this formation into 5 members, the Krol A, B, C, D and E members.

Krol A consists of alternations of thin limestones and calcareous shales, either in parallel bands or in more discontinuous lenticular features with indication of limestone flowage. Locally current bedding and even some ripple marks are visible. A strongly selective cleavage transforms some calcareous shales into pencil slates. Black cherts in thin bands or smaller concretions are typical. *Krol B* is marked by its characteristic soft, thin-bedded purple shales, containing thin layers of dolomitic or siliceous limestones. Being very incompetent the thickness is most variable. These shales are overlain by well-developed cliff-forming limestones—*Krol C.* Locally these limestones show a secondary dolomitization. Above follow cherty limestones alternating with shales of the member *Krol D.* This section is complicated by some white soft sandstones and pockets of gypsum in the limestones. The uppermost Krol member, *Krol E,* generally has a very rugged topography and consists of up to 1000 m of thick-banded grey to creamy-white microcrystalline limestones. Fresh fractures are porcellanous. Often the limestones contain angular and rounded quartz grains sticking out on the weathered surfaces like millet seeds. Locally, red, orange or black shales are intercalated.

After the deposition of the calcareous Krol section a striking change in deposition took place, and the younger beds consist exclusively of detrital, mostly quartzitic rocks. Some earlier investigators have mistaken these quartzites for Jaunsars, but, since the whole sequence is preserved in wide synclinal basins, there can be little doubt about their normal stratigraphical contact with the underlying limestones. These detrital sediments have been called the *Tals*, after the

Tal beds described by MIDDLEMISS in Garhwal (1887). AUDEN distinguishes Lower and Upper Tals.

The *Lower Tals* are characterized by dark, often calcareous greywackes, carbonaceous shales, micaceous shales and some quartzites. The presence of greywackes clearly distinguishes the Lower Tals from somewhat similar Infra Krol beds. Locally ripple marks have been noted. The Lower Tals can be over 1000 m thick.

The *Upper Tals* consist mainly of quartzites with an average grain size of 0.5 mm. Generally arkosic and surprisingly rich in microclines, they vary from a white to a pale green colour. Pebbly sandstones are frequently intercalated, with pebbles of vein quartz and green slates. Current bedding is universal and ripple marks are common. In addition some purple, red-green micaceous shales occur. Some of the shales show vermicular tubes and pockets of sandstones, which, according to AUDEN, may have been caused by subaerial exposure, the mudcracks with upturned edges having been filled with sand. Some calcareous sandstones to dark sandy current-bedded limestones form the top. The Upper Tals form the youngest normal deposits of the Krol belt, while the previously mentioned Eocene Subathus occur below the Krol thrusts and belong to a more southern autochthonous facies belt.

In spite of the absence of metamorphism in most of the Krol belt rocks the well exposed limestones and shales have yielded no fossils. This fact is most surprising and, as already mentioned, is in line with most of the sedimentary belts of the Lower Himalayas southeast of Kashmir. A lucky finder might still discover fossils in future more detailed investigations, and an approach with different methods—searching for spores and pollen and other microfossils may yield new results. But even so, fossils are certainly extremely rare and this is the greatest handicap for evaluating the stratigraphy of the Lower Himalayan sedimentaries. AUDEN has discovered some poorly preserved shells in calcareous sandstones of the uppermost Tals. WADIA (1953) mentions fragments of belemnites, corals and gastropods with a Jurassic affinity. He also reports plant remains from the Lower Tal carbonaceous shales without, however, giving any source for this information. Some fossils, reported from the Krol limestones have turned out to belong to the transgressive Tertiary Subathus.

Unconnected with the unmetamorphic sediments and/or their epimetamorphic equivalents, a large mass of granite, *the Chor granite*, tops the synclinally arranged Jutogh-Simla beds. This Chor granite belongs to the synclinal granite and gneiss belt which is represented by the Dudatoli-Almora thrust sheet, and will be discussed in a following section. The question has arisen in the Krol belt whether some of the mesometamorphism affecting the more susceptible argillaceous horizons, as for instance some types of Simla slates and the Jutoghs, has been caused by the Chor granite. As we will see in many similar instances, the direct influence of the granite is certainly negligible, and the metamorphism, though selective, is of a more regional type, caused by certain heat fronts, indirectly again related to subsequent granitization. The matter will not be further persued here, the more so since the Chor granite belongs to a major thrust sheet and is only tectonically connected to the underlying Krol sediments.

The fact that topographically higher regions expose rocks with a higher grade of metamorphism than the lower horizons was observed at a very early date in the Himalayas, and R. D. OLDHAM working in the Jaunsar area stated in 1883 "This is but part of the great Himalayan puzzle, that newer beds almost always seem to dip under older, that faults are generally reversed, and that the dip of the beds in their neighbourhood is precisely the reverse of what would be excepted on *a priori* grounds."

AUDEN has outlined three main thrusts in the Krol belt: *the Krol thrust*, bordering the Sub-Himalayas and corresponding to the so called "Main Boundary Fault"; *the Giri thrust*, paralleling the Krol thrust approximately 6-8 km northeast of the former; and *the Tons thrust* in the eastern area south of Chakrata, approximately 15 km north of the Krol thrust. The Krol and Giri thrusts are directed to the south and southwest respectively, while the Tons thrust rises to the north in relation with the north border of the large Dudatoli-Almora thrust sheet. The Tons thrust may actually be the reappearing Krol thrust below the Krol thrust mass (Fig. 46c). The general outline of the main thrusts is visible on the geological map, while for better understanding some of the profiles published by AUDEN have been redrawn (Fig. 47a, b, c). The Section (a) shows a clear evidence of thrust folding. None of the Krol thrusts has actually been formed through large recumbant folds. Careful analysis by AUDEN of the many top and bottom criteria, such as the frequent cross-bedding features, clearly indicates *normal sections* and that we actually have to deal with *proper thrust sheets and not recumbant "nappes"*.

Along the Krol thrust, some Krol limestones are thrust over Upper Siwalik conglomerates, giving a post-Upper Siwalik age for the thrusting, which would correspond to earliest Pleistocene. It is, however, surprising that such late thrusting is not affected by an already existing main drainage pattern, which could be expected in the Lower Himalayas at the beginning of the Quaternary. There is no evidence that the Krol thrust has been deflected by a pre-existing topo-

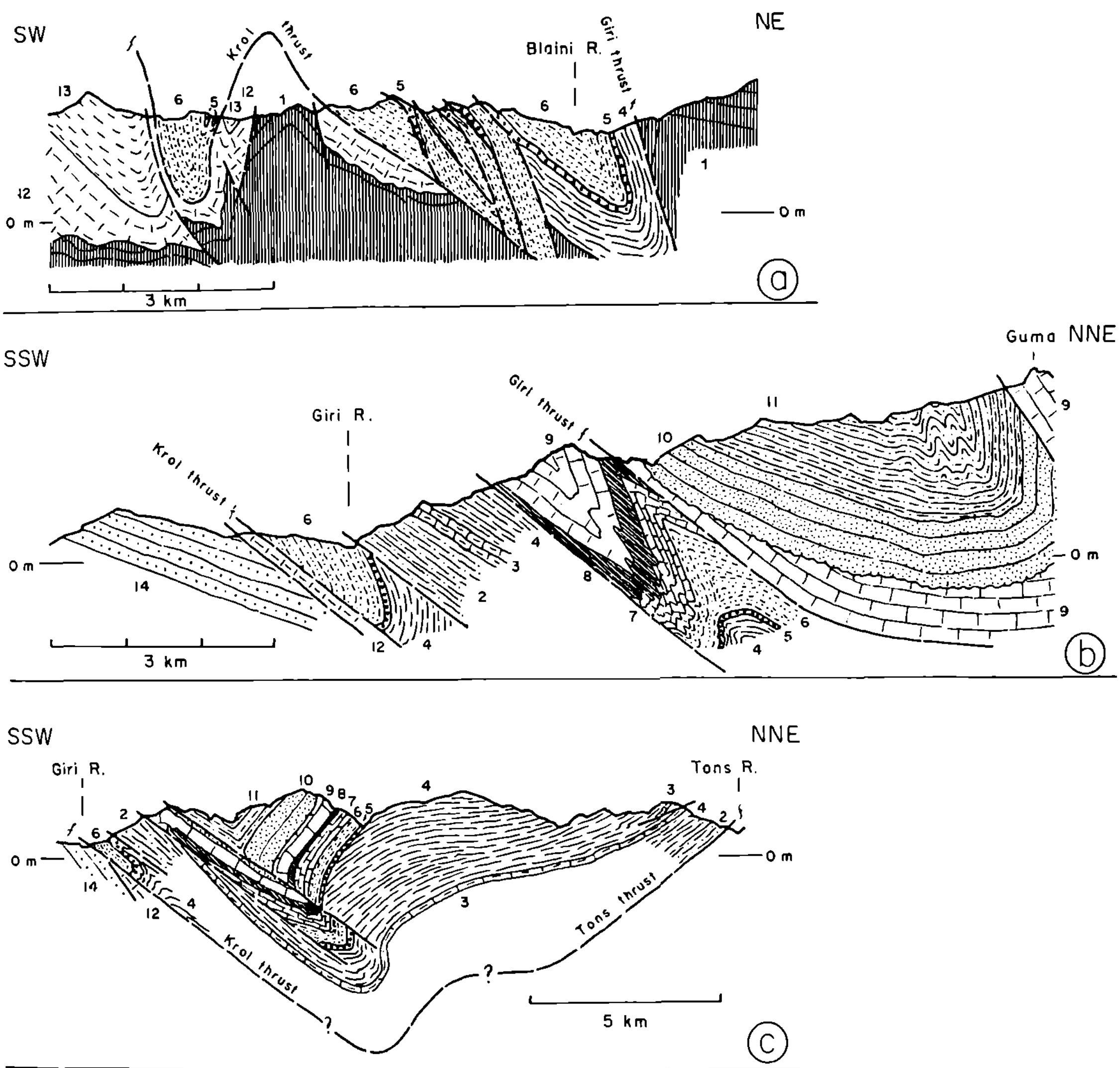


Fig. 47a, b, c *Sections through the Krol belt*, Kumaon Himalayas; redrawn after J. B. AUDEN (1934)

1	Simla slates	8	red shales, Krol B
2	Mandhali	9	Upper Krol limestones
3	Bansa limestone	10	Lower Tal
4	Nagthat and Chandpur	11	Upper Tal
5	Blaini	12	Subathu (Eocene)
6	Infra Krol	13	Dagshai-Kasauli (Murrees)
7	Krol A	14	Nahan (Lower Siwaliks)

graphy, in line with the well-known relief thrusts. This interesting problem will be discussed in a more general way for the whole Himalayan chain.

In 1936 the author paid a short visit to the Mussorie Hills, while AUDEN was mapping in the field. Structurally and lithologically this region is still a replica of the Simla Krol belt (Figs. 48, 49). From here Krol-type outcrops can be followed to the southeast as far as Naini Tal, where they have been studied by HEIM and GANSSER (1939) and AUDEN (1942) and more recently, in connection with the formation of the famous lakes, by THOMAS (1952) who includes unpublished information from AUDEN's mapping in 1942. The Naini Tal region, south of the large Dudatoli-Almora crystalline thrust sheet, is 270 km southeast of the Simla area with its classic Krol sections of AUDEN. Evidently, over such a distance, considerable changes in facies could be expected, and correlation of the various formations is open to some doubt. This difficulty will be even much greater when the thick sedimentary masses of the interior of the Lower Kumaon Himalayas must be considered.

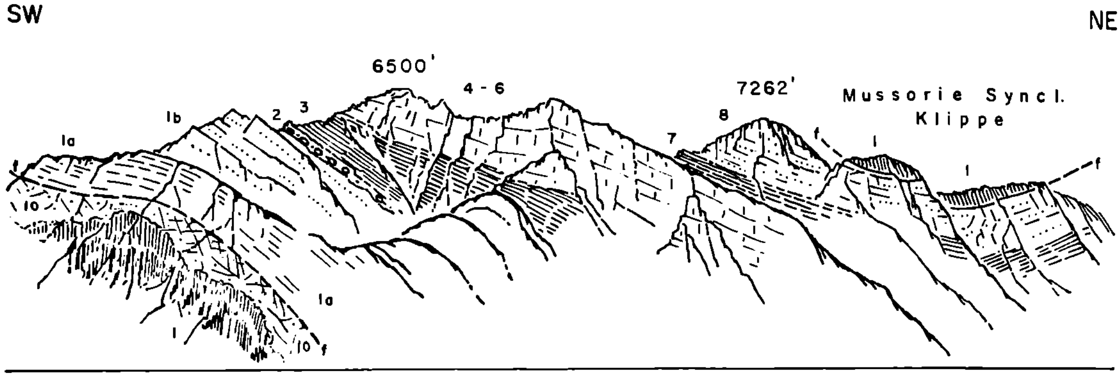


Fig. 48 *The Krol formations in the Mussorie Hills,* Kumaon Himalayas; after A. GANSSER and geology acc. J. B. AUDEN (for legend see Fig. 49)

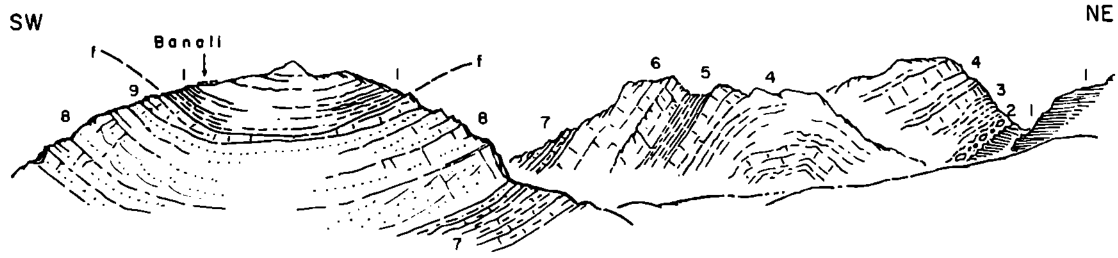


Fig. 49 *Krol outcrops in the foothills of Theri Gahrwal,* Kumaon Himalayas; after A. GANSSER

1 Simla slates, partly autochthonous, partly as Klippen
1a Chandpur slates
1b Nagthat quartzites
2 Blaini tillites
3 Infra Krol
4 Lower Krol
5 red shales
6 Upper Krol limestones
7 Lower Tal
8 Upper Tal quartzites
9 Upper Tal limestones
10 Nummulitic (Eocene) transgressing autochthonous Simla slates

In *the Naini Tal region* the Krol-type rocks are thrust over Middle to Lower Siwaliks as already indicated when discussing the Kumaon Sub-Himalayas (Fig. 50 and Profile 2, Pl. III). Krol sediments are well exposed in the 2600 m high China Peak, the highest elevation of the Naini Tal region. A considerable amount of large scale slumping, responsible for the formation of the various lakes in this region (THOMAS, 1952) masks some of the normal stratigraphical relations.

In the Naini Tal region the oldest outcrops consist of tuffaceous greenstones, altered diabasic rocks followed by quartzites. Normal contacts between the basic rock sequence and the quartzites are not well exposed. The quartzites are thick-bedded, yellowish to green, partly shaly and variegated. They can be over 500 m thick and have been correlated with the Upper Jaunsars, the Nagthat quartzites. This correlation is partly based on the fact that they are covered by a section similar to the Krols. Blaini boulder beds, which should follow above the quartzites, have not been found in their typical development. They may, however, be represented by some conglomeratic greywacke-type sandstones with carbonaceous slates containing some indeterminable plant remains.

A thick section of grey, purple and green shales and slates with intercalations of grey calcareous shales could correspond to the Infra Krol or a more shaly facies of the Lower Krol. They are followed by a relatively thin Lower Krol limestone with conspicuous quartz grains, reminiscent of some of the Upper Krol limestones in the Simla area. Its lower Krol age is defined by the superposed green and red shales with thin dolomitic layers similar to AUDEN's Krol B level and topped by thick dolomitic limestones most likely corresponding to the Upper Krol. No Tal quartzites are known in this section (Fig. 51).

The relatively high Naini Tal mountains bordering the low-lying Siwaliks along a main thrust are full of tectonic complications, and conspicuous post tectonic slips and mass gliding. THOMAS (1952) tried to relate the lakes of the Naini Tal region, a rare phenomenon in the

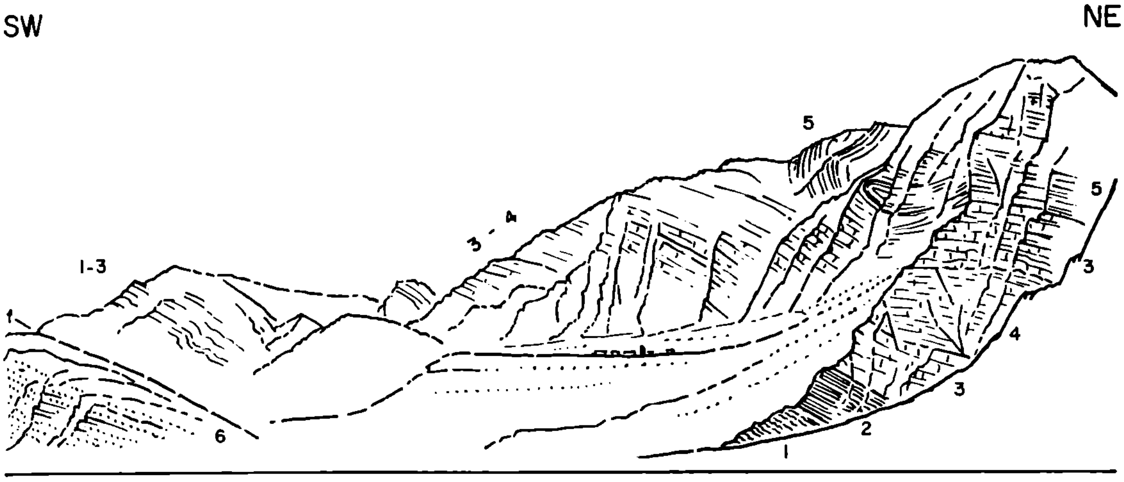


Fig. 50 *Krol formations thrust on Siwaliks,* southern Naini Tal region, Kumaon Himalaya; after A. GANSSER

1 green shales } Infra Krol?
2 red and green shales and dolomites } Infra Krol?
3 dark grey dol. limestone, Lower Krol
4 yellow brown shaly limestone } Upper Krol?
5 alternation shales and limestones } Upper Krol?
6 Siwaliks
f Main Boundary Fault

Himalayas, to such post-tectonic slumping and mass gliding or gravity gliding. We have here a fine example of how gravity gliding can follow major tectonic effects as a kind of adjustment movement but not be the prime cause of the structural picture. THOMAS was able to prove how secondary fracture lines, strongly oblique to the main boundary thrust, do coincide with a change in direction of the latter. This change may have been caused by a forward-thrusting of the Krol nappe over an erosional gap, and structural disturbances in the Siwaliks and the secondary fracture lines could well be related tear faults (Fig. 42).

Deoban-Tejam belt

The sedimentary belt following south of the main thrust of the Higher Himalayas can be traced from the Simla area in the northwest to the

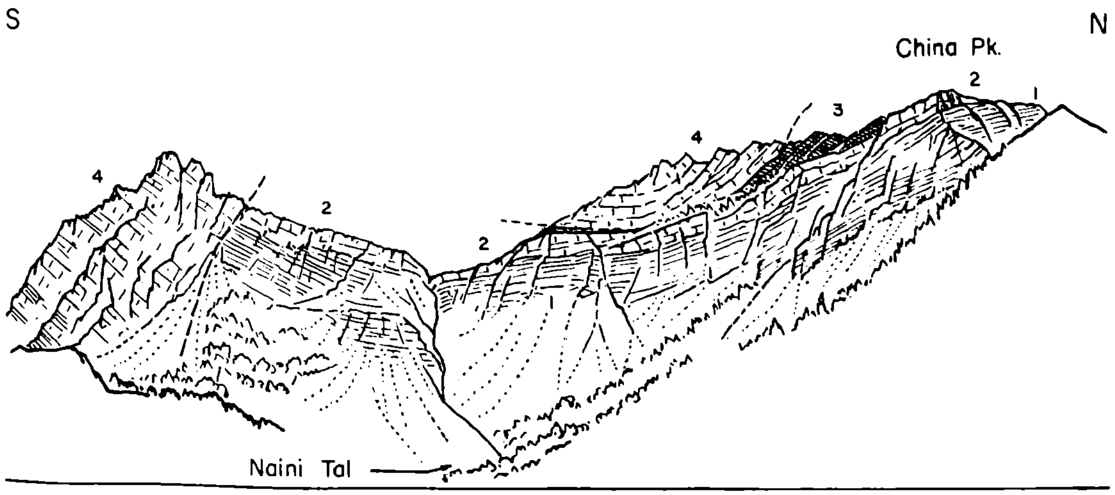


Fig. 51 *The geology of China Peak,* Naini Tal, Kumaon Himalaya; after A. GANSSER

1 green (tuffaceous) shales
2 Lower Krol limestones
3 green and red shales with dolomites
4 Upper Krol limestones

border of Nepal in the southeast, for about 350 km. It is a belt of enormously thick limestones and dolomites topped by thick sections of quartzites, all without any conspicuous metamorphism. So far no fossils have been found, except the stromatolitic structures in the southeastern branch (Badolisera belt), characteristic for rocks of late Precambrian to early Palaeozoic age. Lithological correlations are very risky, since none of the better known formations are strictly comparable with these sections. New names have therefore been introduced as long as no convincing correlation or age determinations are possible.

The traverses of HEIM and GANSSER (1939) have recently been extended to the southeast into the region of Pithoragarh and the Kali River, which forms the border with Nepal (MISRA and VALDIYA, 1961 b; VALDIYA, 1962 b). Of great importance is the find of *stromatolites* in the calc-zone of Pithoragarh, which give some hints of the possible age relation. But being found in an inverted position, suggested also by similar indications in the quartzites, they have considerably complicated the structural picture (Fig. 52).

In the western interior part of the Kumaon Lower Himalayas, the inner sedimentary zone is represented by the *Deoban limestone* north of the Krol belt (Deoban Peak north of Chakrata). The limestones are pale grey, often dolomitic, sometimes oolitic and contain cherty concretions which locally are developed in the form of stromatolites. OLDHAM as early as 1883 mentioned closely chambered shells in the cherty limestones. The position of the Deoban limestones is still uncertain; according to investigations by WEST and AUDEN they are related to the Jaunsars. Mandhali boulder beds are reported to grade into Deoban limestones and contain the corresponding limestone as boulders. Deoban limestones are certainly pre-Blaini (PILGRIM and WEST, 1928). Most likely they can be correlated with the Kakarhatti limestones in the lower Simla slates and the Shali limestone of the Shali window. Stromatolites have been reported in both limestones, and as far as we know, correlations on such characteristic features which in late Precambrian to Cambrian rock sequences have a relatively restricted range, are well founded.

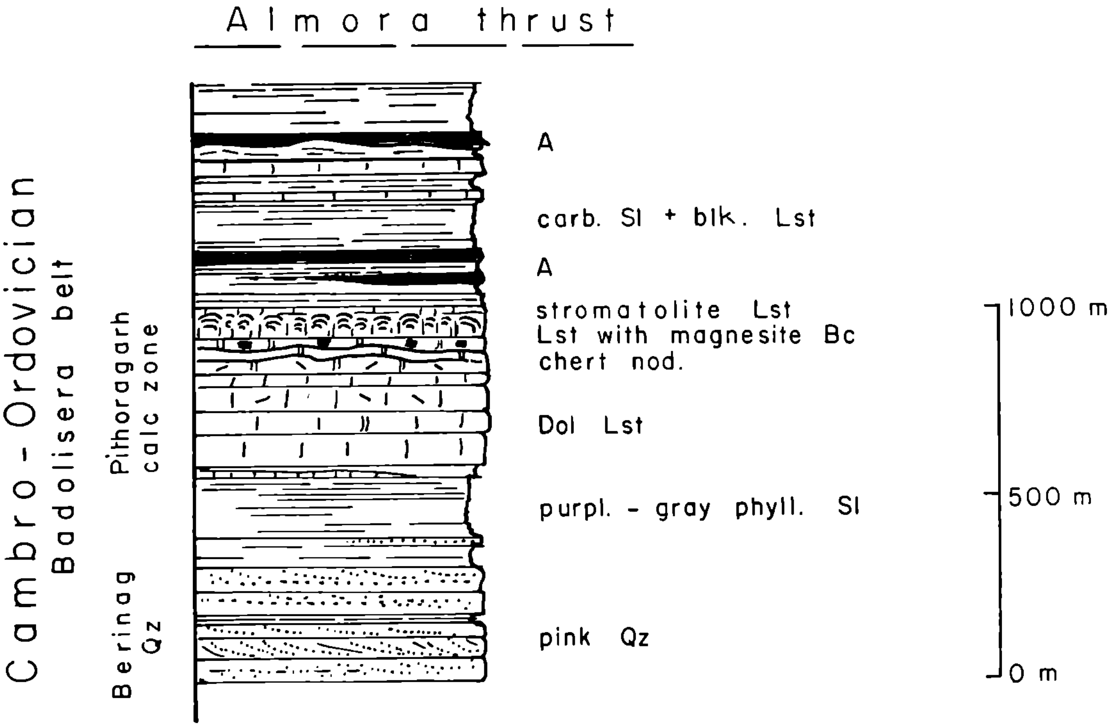


Fig. 52 *Stratigraphy of the Badolisera-Pithoragarh area,* Kumaon Himalayas; compiled after MISRA and VALDIYA (1961, 1962) and HEIM and GANSSER (1939) (the field section is inverted)

The Deoban-Tejam zone in the eastern Lower Kumaon Himalayas can be divided into two belts, separated by the Askot-Bajnath crystalline thrusts. In the south we distinguish the *Badolisera-Pithoragarh* zone (HEIM and GANSSER, 1939; VALDIYA, 1962), in the north the *Chamoli-Tejam* zone (see section 1, 2, 4, Pl. III).

The Badolisera-Pithoragarh zone follows just north along the north-thrust border of the Almora-Dudatoli crystalline. The deepest outcrops, visible in a steep, fan-shaped "anticline" without corresponding limbs, consist of highly contorted thin quartzites with dark grey slates grading upwards into more greenish and reddish types. Northwards and apparently upwards some limestones begin, alternating with quartzites. Sills of dioritic amphibolites are intercalated in the slates and quartzites. The base of the limestones is characterized by green sericite schists, not unlike the Dalings of the eastern Himalayas. The limestones show a peculiar fine banding of dolomitic and calcareous seams, giving to the rock a typical white and grey striped appearance. They extend for a thickness of 500 m, with intercalations of peculiar layers of a very coarse spathic magnesite, often brecciated or with radial and spherulitic patterns, and associated with talcose layers. This very constant horizon can reach a thickness of over 50 m. A similar magnesite horizon has been reported by VALDIYA from the calc-zone of Pithoragarh more to the east, where it accompanies the remarkable stromatolite limestones.

A thick section of quartzites follows over the dolomitic limestones. Repetitions of carbonate rocks do occur, but considering the tectonic complication in this area, they may not be of a stratigraphic order. Similarly the true thickness of the quartzites is difficult to judge, but at least 1000 m are present. They are often thick-bedded and can be locally conglomeratic, with quartz pebbles up to 25 cm size. Generally the quartzites are coarse-grained. Northwards, towards Berinag, where the sediments are overthrusted by the Askot crystalline thrust, the complexity of the quartzite section is well exposed; intercalations of sericite schists, conspicuous green chloritic schists and thick bodies of limestones and dolomitic limestones are directly interbedded in quartzites. This whole section is separated from the more southern quartzite zones by a local thrust zone. In the eastern extension, north of Pithoragarh, VALDIYA describes the eastern continuation of the Berinag quartzites, a section of sericitic quartzites with purple phyllites at its base and intercalated with chloritic schists. Just below the crystalline thrust there are outcrops of schistose amphibolites with sericite-biotite schists. Some of these amphibolitic zones resemble altered dioritic sills. It is an interesting fact that such *amphibolitic intercalations are frequently present along thrust zones.* They actually follow the thrusts and seem related rather to the latter than to the underlying sediments with which they are, however, mostly in normal, interstratified contact. This fact brings us to one of the most salient problems related to the large crystalline thrust masses of the Himalayas, where rarely a clear cut thrust line is visible in the field. We will discuss this question in a later chapter.

In the *Badolisera-Pithoragarh section* (Fig. 52) MISRA and VALDIYA have made the interesting observations that the arched laminae of the stromatolitic structures are *convex downwards.* This very significant fact suggests that the stromatolitic limestones and all the horizons normally related to it are *stratigraphically inverted.* Observations made on cross-bedding and ripple marks of the quartzites of the Pithoragarh zone indicate again inverted sections, in line with the stromatolitic calc-zones. While some sections are undoubtedly inverted, I would not follow VALDIYA in applying this concept to the whole sedimentary section of the inner zone in the Lower Kumaon Himalayas (VALDIYA, 1962 b). Local tectonic complications are certainly present; imbrications and minor thrusting play an important role, in spite of the often rather gentle general tectonic picture. In the Badolisera-Pithoragarh zone we probably have two detrital sedimentary sections—a lower one which is rich in variegated schists and sericitic quartzites, and an upper one, separated by the limestones and dolomites, which is more uniformly quartzitic and often contains quartz pebble horizons. Towards the northern thrust as seen for instance in the Berinag region, it is most probably the lower quartzites that form the tectonically upper horizon. Here an *increase in metamorphism upwards* is recognizable by an increase in sericitization and the incoming of some biotite. As we will see later, particularly in the eastern Himalayan ranges, an increase upwards in metamorphism does not yet indicate that inverted sections are present. It may be the case in the Pithoragarh region, but is certainly not regionally applicable.

In the *Chamoli-Tejam zone,* investigated by HEIM and GANSSER (1939), and AUDEN (1949, W. Chamoli), the sedimentary sections are considerably thicker than in the Badolisera belt and the tectonic picture somewhat less complicated by secondary disturbances. In spite of this fact the normal stratigraphical sequence is still uncertain, mainly because of the hitherto complete lack of fossils, and the meagre indications of top and bottom criteria. The enclosed stratigraphical column must therefore be interpreted accordingly (Fig. 53). The Chamoli-Tejam zone is bordered in the south by the small thrust-like inliers of Askot-Bajnath, which, west of Kapkot, are nearly connected to the main thrust zone of the Higher Himalayas which form the north border. Along the upper Ganges River (Alaknanda at Chamoli) the Chamoli-Tejam zone is further complicated by a small crystalline remnant south of Chamoli, separating the broad sedimentary anticlinoria north of Chamoli from a most complex section to the south where large masses of basic rocks are involved (Sect. 4, Pl. III).

The deepest outcrops of the Tejam zone can be studied between Tejam and Kapkot in the Sarju and Ramganga Rivers. They consist of thick-bedded *dolomites and crystalline limestones*, and some of them are actually fine marbles with sericitic seams, breaking into thin plates. Near

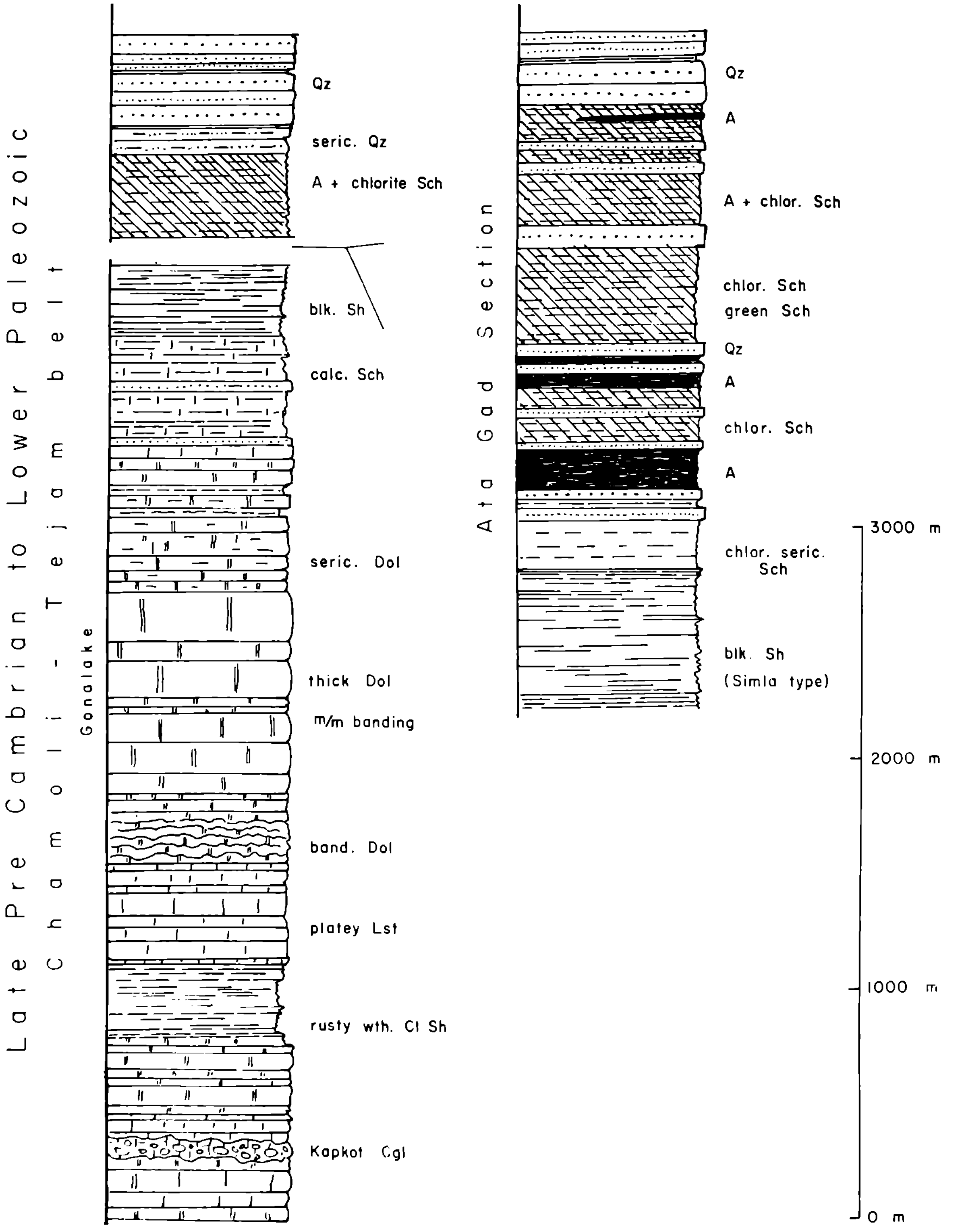


Fig. 53 *Stratigraphy of the Chamoli-Tejam zone*, Kumaon Himalayas; compiled after HEIM and GANSSER (1939) (the Ata Gad section which seems inverted in the field, has been drawn normal in this section)

Tejam and Kapkot a peculiar conglomerate is intercalated in the dolomites. In a matrix of schistose marbles occur pebbles and boulders of predominant quartzites, limestones, and reddish sericitic sandstones. Some of the quartzite boulders can measure up to half a metre, but most are smaller than fist size. Marbles and dolomites follow above the conglomerate and are frequently interbedded with dark argillaceous slates or phyllites which can locally increase to form quite thick horizons. North of Tejam this section seems practically without disturbance, and dips at an average of 30° to the NE (Fig. 54). Under this assumption, the normal thickness of the calcareous section would amount to the enormous figure of 5500 m. Concealed minor thrusts, along the intercalated phyllitic layers could have been easily overlooked and thus reduce this amount. Nevertheless, several thousand metres may actually be present.

In the western extension, where the lower part is not exposed as in Chamoli and in the Gona Lake region, over 1500 m are normally visible. In this area the calcareous section is similar to that of Tejam, represented by dolomitic limestones, dolomites and fine marbles, with dark slates and calcareous schists as intercalations. Some of the massive-looking dolomitic limestones consist of a very fine banding of millimetre-thick yellowish weathered grey siliceous dolomites and white microcrystalline limestones. The banding can be observed over large sections and represents a rhythmic type of sedimentation of great dimensions. The siliceous dolomites have a silica content of more than 50% while only 8% is present in the limestones. In some horizons the thin bands are minutely folded. In the Alaknanda Gorge north of Chamoli the carbonates form large anticlines (Section 4, Pl. III) with a most conspicuous steep north-dipping fracture cleavage.

Compared to the calcareous zone of the already discussed Badolisera-Pithoragarh region, the carbonates of the Tejam zone are more uniformly constituted, contain less argillaceous and quartzitic intercalations, and are considerably thicker.

The dolomites and limestones of the Tejam zone are invariably overlain by *quartzites*, with intervening phyllites. The quartzites are mostly sericitic, and, similar to the sections already observed in the southern sedimentary belt, an increase in metamorphism can be noted towards the top and in most cases towards the main crystalline thrust mass. This fact is visible in the intercalated schistose sections. The increase of such argillaceous sediments alone is, by their selective metamorphism, responsible for an apparent higher metamorphism, but even within the argillaceous quartzites an increased metamorphism is noticable, such as the presence of biotite, garnets and even some kyanite which are missing in the normal less metamorphosed schistose zones within the quartzites. Particularly towards the Chamoli region many instances can be noticed where it is difficult to distinguish between the crystalline rocks of the main thrust sheet and the underlying quartzitic sediments (Fig. 55). As we will see later, large bodies of quartzites are actually intercalated *within* the crystalline thrust sheets.

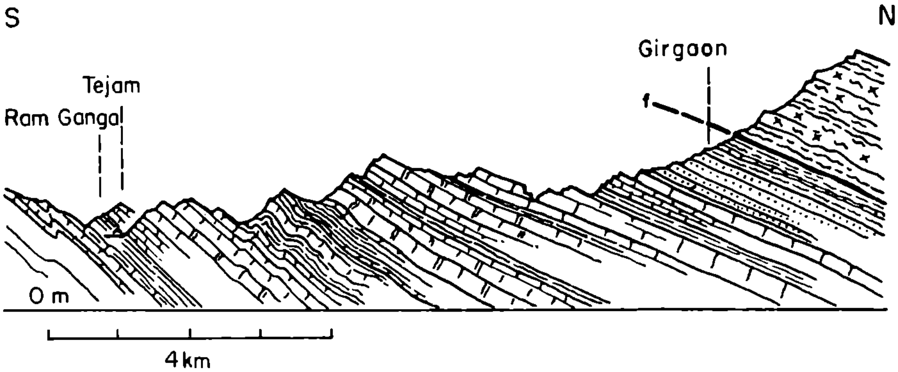


Fig. 54 *The thick carbonate section between Tejam and Girgaon* (Chamoli-Tejam zone), Kumaon Himalayas; after HEIM and GANSSER (1939)

South of the Chamoli area and just south of Karnaprayag thick zones of *basic schists* occur between thin quartzite beds. Along the Ata Gad, a southern arm of the Pindar River, they form near-continuous outcrops for 7 to 8 km (Fig. 53). Following above normally north-dipping quartzites, situated not far north of the large Dudatoli thrust mass, one notes a thick section of green chlorite-amphibolite schists, with intercalations of normal amphibolites, which, based on their rich content of albite/oligoclase, may have been of spilitic origin. Epidote is generally present. Thin and thick quartzites are irregularly interspersed. Upwards, assuming a normal section from south to north, follow chlorite-sericite schists

and then a most conspicuous section of black clay slates, some types resembling black roofing slates, practically without sericite. The general aspect is not unlike some of the black slaty parts of the Simla formations. The upper contact of the slates is faulted, with more quartzitic horizons following up-river. The actual position of the slates is not clear. They seem, from the available

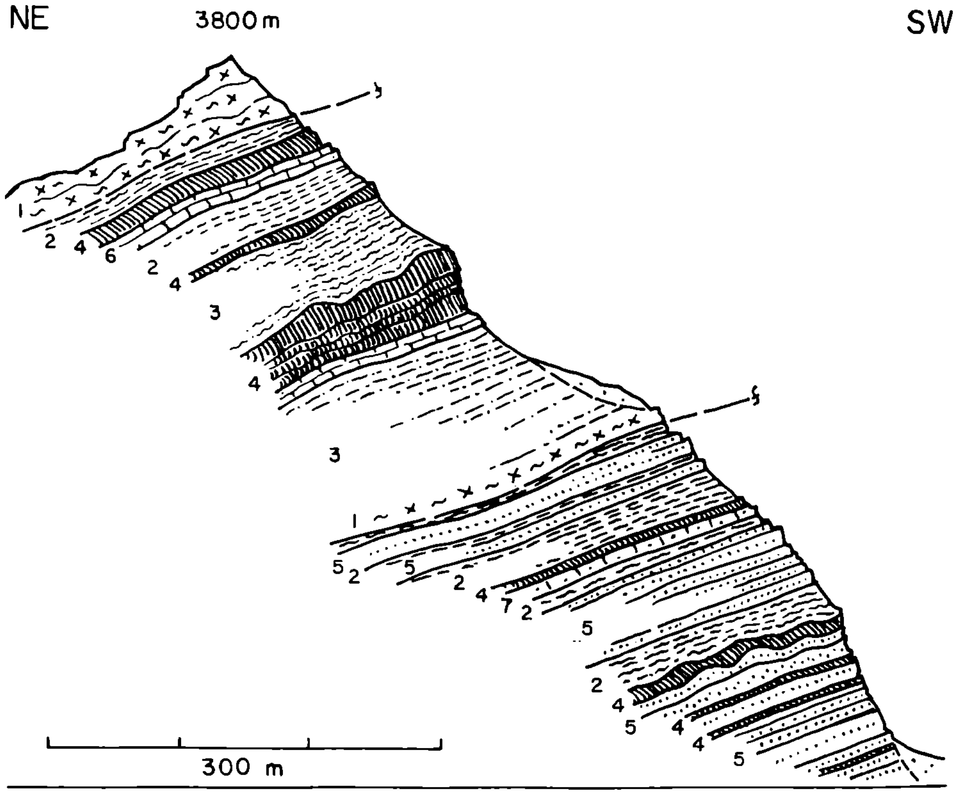


Fig. 55 *The increase in metamorphism towards the Main Central Thrust in the section of the Kuari Pass.* Kuamon Himalayas. Border of Chamoli-Tejam zone with the crystalline thrust; redrawn after HEIM and GANSSER (1939)

1 granite-gneiss
2 mica schists
3 garnet schists
4 amphibolites, epidiorites, partly chloritized
5 quartzite, becoming sericitic upwards
6 grey banded marbles
7 sandy limestones
f main and secondary thrust

field information, to lie between the calcareous sections and the quartzites and basic volcanics. The good outcrops along the new motor road to Badrinath must have provided a wealth of new information which unfortunately is not yet available to the writer. This area has recently been traversed by J. F. SEITZ of the United States Geological Survey, but so far only a very brief indication has been published in the directors report for the year 1959 in the Records (Rec. geol. Surv. India, 1962). SEITZ (personal information) was apparently able to confirm much of the earlier surveys, but had apparently no time to publish his new results.

Age, correlation and structure

The great thickness and rather constant development of practically unfossiliferous and only slightly metamorphic sediments, where the metamorphism seems to increase from the topographically lowest exposures to the top horizons, is a unique feature in the inner part of the Lower Kumaon Himalayas. It has been variously attempted to correlate this large heap of sediments with other known sections; the ages thus computed vary from Precambrian to Mesozoic. At a first glance correlation with sediments of the Krol belt seems feasible. This is certainly not the case for the calcareous sediments where stromatolitic structures were noted, and here I would agree with MISRA and VALDIYA (1961, 1962) who correlate the Pithoragarh carbonates with the Deoban-type limestones. The quartzites are then comparable to the Jaunsars. This would make sense if the section were not inverted. Some of the sedimentary sequence is however

certainly inverted, and therefore some of the quartzites older than the carbonates. Since VALDIYA accepts PILGRIM and WEST's stratigraphy (1928) placing the Jaunsars below the Simla slates (changed later by WEST, 1931), the lowest quartzites could correspond to those Jaunsars. Following AUDEN (1934), and the *Stratigraphic Lexicon* (1957), I would place the Jaunsars *above* the Simla slates, and thus above the Deoban-type limestones. We have, however, seen that quartzites occur below and above the carbonate sections. This clearly shows how uncertain these correlations still are, and one needs much more detailed work and better stratigraphical control in order to unravel the sedimentary geology of the Lower Kumaon Himalayas.

Equally vague remains the structural interpretation. The surprising fact that a large part of the Badolisera-Pithoragarh belt occurs in an inverted position is certainly intriguing, and one wonders how much of the other large sedimentary sequences in the Chamoli Tejam belt are equally inverted. No certain proof of this has been noticed in these sections, and the local complications, particularly in the southern belt, do not necessarily suggest a continuation of such an inversion into the northern belt. VALDIYA's assumption of a huge recumbant anticlinal fold thrust from north to south for over 180 km is very difficult to visualize. His tectonic section on page fortyfive (1962 b) has certainly not the appearance of the reversed limb of a large thrust fold. He furthermore correlates this thrust mass with the Krol thrust of AUDEN. AUDEN (1934) has clearly shown that the various Krol thrusts are *not* recumbant thrust folds, but upright thrust sheets. Somewhere between the western and the eastern Kumaon Lower Himalayas the whole Krol thrust mass must turn from a normal to an inverted position. The frontal Krol thrust sheet of Naini Tal is upright. I certainly agree with VALDIYA that good arguments for inverted sections and most striking inverted metamorphism do exist. Even the quartzite sections show that the metamorphism increases upwards towards the large crystalline thrust masses. That a similar effect seems to be present within the crystalline thrust will be shown in the next section. We touch here one of the most problematic facts of the whole Himalayan range.

If we compare the Tejam calcareous zone with the definitely autochthonous to parautochthonous outcrops of the Simla slates with transgressive Eocene in the Theri State just north of the Ganges (AUDEN, 1937 b) (Fig. 48), a striking lithological as well as structural difference becomes evident. This difference can be explained by assuming an allochthonous thrust character for the Tejam zone. We may actually have here a large lower thrust sheet below the main crystalline thrust. The base of this assumed thrust is however nowhere exposed.

Almora-Dudatoli thrust sheet and the smaller Baijnath and Askot remnants

We have already mentioned that the inner sedimentary zone of the Lower Kumaon Himalayas is separated by the large Almora-Dudatoli thrust sheets from the frontal Krol thrusts of Naini Tal, and that this inner sedimentary zone is subdivided by two smaller thrust remnants, the Askot and the Baijnath thrusts.

The Almora thrust sheets can be followed into western Nepal where their equivalent is the Dandeldura *massif* of HAGEN (1959 a), interpreted by him as parautochthonous crystalline. Westwards, it reaches the Ganges River (AUDEN's Garhwal nappe, 1937) from where, over some small isolated klippen, it can be traced south of the Deoban area towards the large thrust mass of the *Chor granite* in the Simla region.

The Almora thrust forms a huge crystalline syncline, as indicated on the geological section (1, 2, Pl. III and Fig. 61). The minor thrust remnants show the same synclinal features. From the section it is evident that the composition of the Almora crystalline is a most complex one and that the two limbs do not correspond to each other either lithologically or in thickness. A marked change in the crystalline composition is evident from north to south. Following section 2 (Pl. III) from Naini Tal over Almora to its north end at Jandi we can recognize the main rock types described below.

After the Krol thrust sheet of Naini Tal a peculiar, steep zone is met at Bhowali with some quartz conglomerates, highly crushed quartzites and conspicuous green amygdaloidal epidote diabases. To the south, the lower quartzites of the Naini Tal form a thrust contact, and to the north begins the large crystalline mass of Almora. This mass is evidently thrust, as indicated on our section, but, and here again we note the general difficulties in the Himalayan geology, it is not possible to locate the thrust exactly in the field since no sharp contacts can be observed coincident with a marked difference in metamorphism. The Bhowali basic rocks are followed, at a surprisingly constant northerly dip, by quartzites with dolomitic intercalations. These quartzites, in themselves rather micaceous, are overlain by mica schists, grading upwards into some schistose gneisses. The base of the lower part of the Almora thrust mass has been arbitrarily placed at the base of these mica schists. Schists and gneisses are followed by a characteristic gneissose quartz porphyry (Ram Gad) overlain by a sedimentary section with quartzites, phyllites with intercalated amphibolites and dolomite and massive marbles. These again are overlain by sericite phyllite, grading without any sharp break into sericite schists. At the base of these schists

a second thrust has been assumed and is indicated on the general section. From this thrust northwards the constantly northward-dipping sequence shows a gradual increase in metamorphism. The schists have some tabular sericite quartzite intercalations, characterized by the perfect orientation of their quartz grains with strictly parallel layers of muscovite and sericite, stretched in the 'a' direction (SW-NE) with a very marked striation. Upwards the sericite schists grade into muscovite schists, gradually garnets appear, with centrally arranged inclusions of quartz and magnetite. Then biotite is formed and we have now muscovite-biotite-garnet schists. Further up in the section, feldspars begin to sprout and the schists are changing into muscovite-biotite gneisses. Strikingly clear twinned albites occur in these rock types. An increase of alkali feldspars leads to the granite gneisses, widespread in the region of Ranikhet. They contain no biotite, but a slightly greenish phengitic muscovite.

South of Almora, instead of the granite gneisses, there are outcrops of a coarse- to medium-grained muscovite-biotite granite—the *Almora granite.* It appears in a thick lenticular sill-like position, and does not cut through its surrounding gneisses and schists. It seems to correspond to a syngenetic granitization without discordant offshoots in the form of dykes and apophyses. The massive granite includes frequent xenoliths of psammitic biotite rocks. This granite has been traced recently into the *Champawat* area in the southeast where it was described in detail by VALDIYA (1962 c). Here the main rock is predominantly a granodiorite with later intrusions of a coarse granite. As in the Almora granite, xenoliths rich in biotite are very frequent. South of the granodiorite gradually lower metamorphic belts appear. Bordering the granodiorites to the south a belt of augen gneisses follows, grading southwards and downwards into biotite schists and phyllites. The latter are thrust over quartzites. This sequence is very similar to the section south of Almora. The Champawat granites and granodiorites are regarded as intrusive. Compared to the augen gneisses, they show idiomorphic zircons, while the gneisses have characteristically rounded, possibly reworked zircons, indicating a possible granitization of meta sediments. To the northeast another granite mass outcrops in the Dudatoli region — the *Dudatoli granite* of MIDDLEMISS (1887). The eastern extension of the Almora thrust mass has been investigated by AUDEN, but apart from short notes, no comprehensive report has been published.

The north border of the Almora granite is again characterized by a sudden decrease in metamorphic grade. The granites are bordered by granitic gneisses with broken feldspars, resulting from stress influence, and grade into lenticular gneisses with quartzites and schists. Low-grade schists predominate, topped by schistose graphitoid quartzites of strikingly black appearance. Such graphitic horizons seem to form significant marker beds in the crystalline thrust sheet and may correlate with a large extent of black carbonaceous slates which follow north of the Champawat granite and granodiorite with a remarkably sharp contact and a conspicuous low-grade metamorphism (Fig. 56).

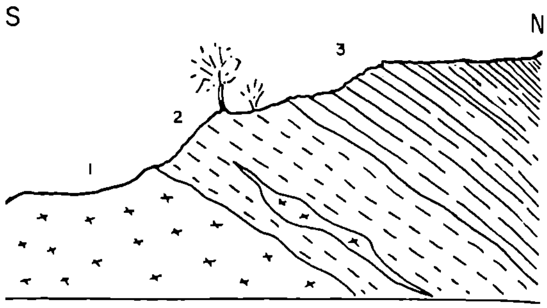


Fig. 56 *Contact of Champawat granite with northern slate zone.* Almora thrust zone Kumaon Himalayas; after K. S. VALDIYA (1962)

1 Champawat granite
2 schistose phyllites
3 carbonaceous slates

The graphitic zone, covered by some garnet schists north of Almora, forms the highest horizon of the large Almora crystalline syncline. From here to the north, the constant northerly dip has changed into an equally constant southerly dip. We find, however, no equivalent of the Almora granite, but several intercalations of muscovite-biotite-alkali-feldspar gneiss, whose frequent very large orthoclases (up to 8 cm) give it the character of a typical augen gneiss. Diabasic amphibolite sills are sometimes intercalated with fine-grained biotite-psammite gneisses. No decrease in metamorphism can be observed on this northern part of the large Almora thrust sheet except for the presence of some mica schists and quartzites at the base of the thrust. The thrust contact on its northern edge is much better outlined, and we have no difficulties in tracing the actual thrust line in the field (Fig. 57).

North of the large Almora-Dudatoli thrust mass we have already mentioned two smaller synclinal thrust relics—in the southeast the Askot thrust and in the northwest the Baijnath thrust mass. They separate the Badolisera sedimentary zone from the Tejam sedimentary belt.

The crystalline zone of Askot is very assymetric, with a flat thrust to the south and a steep to vertical north border (see section 1, Pl. III). On its south side it borders the marked metamorphic schistose quartzites of Berinag which are overthrust by gneisses alternating with thin zones of

sericite-chlorite schists. Several dioritic sills are intercalated, more or less altered to amphibolites. Along the Ramganga River a steep sedimentary zone seems to separate a southern thrust zone from a northern one, as indicated on section 1, Pl. III. A large mass of tourmaline bearing muscovite-alkali-feldspar gneiss forms the bulk of the northern thrust mass which borders with a very steep contact the quartzites of Askot (Fig. 58). Near the contact the gneisses change into contorted garnet schists with large clearly rotated garnets. Just at the contact chloritoid phyllites are intercalated in the garnet schists. Dioritic amphibolites form the actual contact zone, and occur also between the underlying quartzites of Askot (Fig. 59). The contact is thus drawn above the dioritic sills. These dioritic sills, more or less altered to amphibolites, show a surprisingly constant composition and accompany here too the base of the crystalline thrust masses. Less frequent along the Almora thrust, they border the Askot and Baijnath masses and

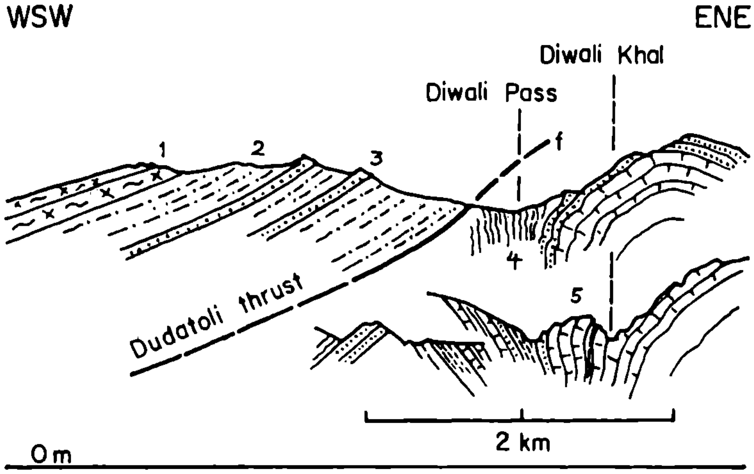


Fig. 57 *Sharp thrust on the north side of the Almora crystalline mass.* (Dudatoli thrust) Kumaon Himalayas; redrawn after HEIM and GANSSER (1939)

1 augen gneiss
2 garnet-mica schists
3 sericite quartzites
4 slates and shaly limestones with some green schists
5 limestones with dolomites

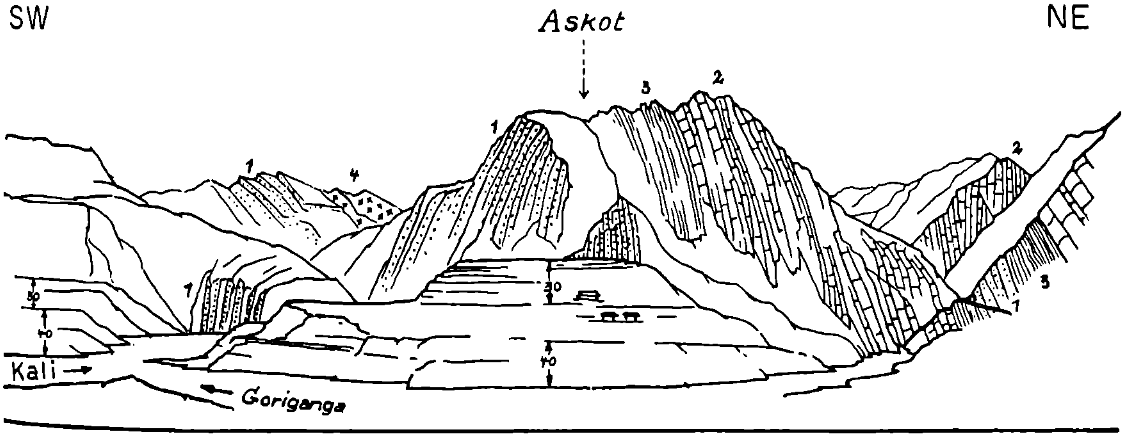


Fig. 58 *The steep zone of Askot* adjoining the north side of the steep Askot thrust. Kumaon Himalayas; after A. GANSSER (1939)

1 quartzites
2 well bedded limestones
3 slates and schists
4 gneiss of Askot thrust mass

note the well outlined terraces at the confluence of the Goriganga with the Kali River

are commonly found at the base of the main thrust of the Higher Himalayas.

The Baijnath thrust mass is similar to the Askot thrust mass, though somewhat less compressed (Fig. 60). Its southern, as well as its northern border are accompanied by dioritic sills. The regularly north-dipping southern part is much thicker than the south-dipping northern part— a perfect replica of the tectonic style of the large Almora-Dudatoli thrust mass as well as of the Askot thrust mass. North of Baijnath occur schistose carbonaceous layers similar to the graphitic horizons in the central and highest part of the Almora thrust. The large basic sill, just north of Sirkot, consists of the usual dioritic amphibolites with a zone of uncommon tourmaline-epidote amphibolites. After this sill follow granite gneisses and then a large body of granite bordered by basic sills and overlain by more gneisses and schists. It seems possible that a major thrust is concealed in the basic sills of Sirkot, dividing the southern part of the thrust mass similar to the Askot mass and recalling again the structural picture of the southern part of the Almora thrust. In a comparison of the various thrust masses, the Almora-Dudatoli, the Askot and Baijnath thrusts, the structural similarity is striking. All are assymetrical; all have a much thicker southern part, usually doubled by a secondary thrust; all generally disclose an undefined southern contact, with hardly any change in metamorphism, contrasting with a better defined northern thrust contact. These facts are schematically indicated in Fig. 61.

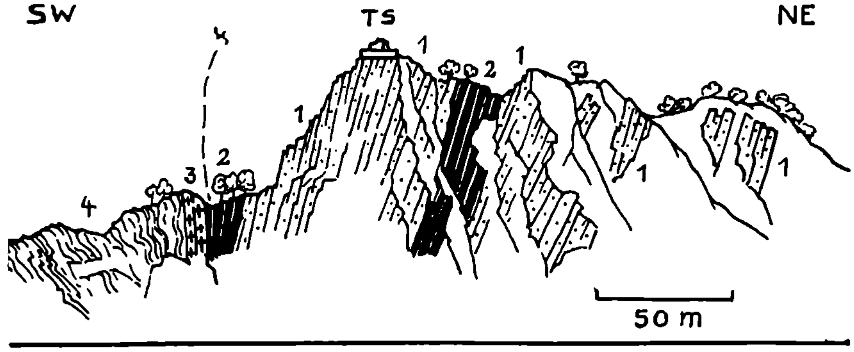


Fig. 59 *The northern contact of the thrusted Askot crystalline with the sediments of the Chamoli Tejam zone,* at Sandeh, NW Askot; after A. Gansser (1939)

1 well bedded quartzites
2 amphibolite sills
3 gneiss
4 garnet-sericite schists with chloritoid
f main thrust

HIGHER HIMALAYAS OF KUMAON

In the Kumaon Himalayas the southern border of the Higher Himalayas is well defined, geologically and morphologically. It coincides with the main thrust, and, after crossing this major structural element, one enters the high mountain range. This sudden rise to the higher mountains

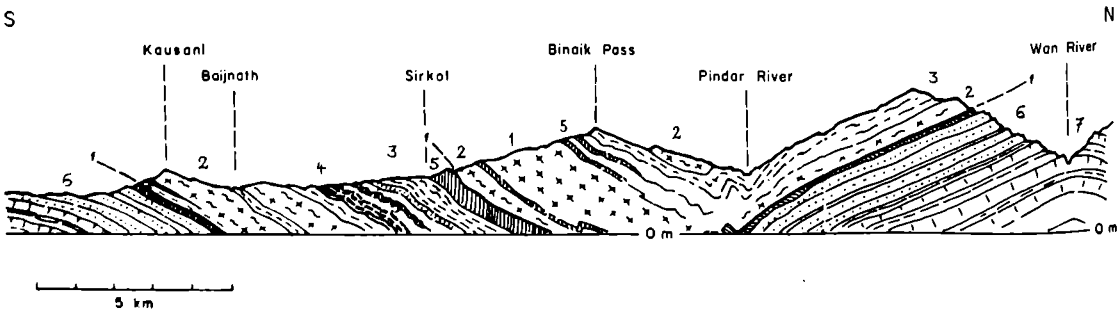


Fig. 60 *Section across the Baijnath thrust mass,* north of Almora. Kumaon Himalayas; redrawn after Heim and Gansser (1939)

1 granite
2 granite gneisses
3 mica schists
4 graphitic schists
5 dioritic amphibolites (sills)
6 quartzites
7 crystalline limestones, Tejam zone

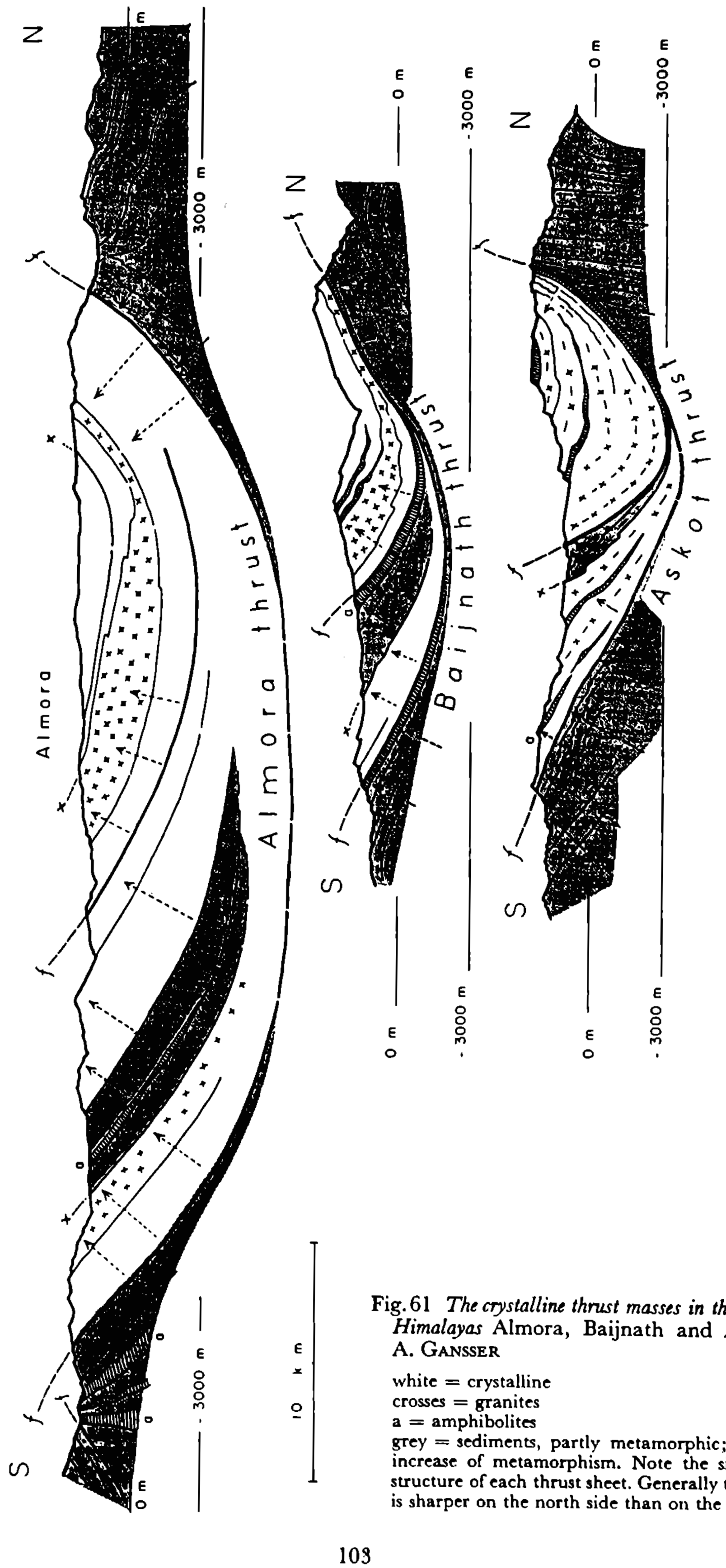


Fig. 61 *The crystalline thrust masses in the Kumaon Lowe Himalayas* Almora, Baijnath and Askot; original A. Gansser

white = crystalline
crosses = granites
a = amphibolites
grey = sediments, partly metamorphic; arrows indicate increase of metamorphism. Note the similar assymetric structure of each thrust sheet. Generally the thrust contact is sharper on the north side than on the south side

is rather abrupt, and is clearly visible when viewing the high range from the hills of the Lower Himalayas (Panorama Nr. 1 and 2, Pl. IV). The northern limit, towards the Tibetan or Tethys Himalayas is less clear. The slope from the high mountains towards the Tibetan high plateau is more gradual, and, since from the main thrust to the north we actually have one continuous sequence of sediments, the geological limit is equally vague. It is arbitrarily placed where the fossiliferous sediments of the northern slopes begin their independent tectonics, which roughly coincides with the Middle Palaeozoic outcrops. The enormously thick argillaceous deposits embracing the span from late Precambrian to the Lower Palaeozoic are tectonically conformable to the underlying metamorphics, which form the base of the Higher Himalayas.

Crystalline thrust

The major element of the Higher Himalayas is the *Main Central Thrust*, which in magnitude surpasses the equally important Main Boundary Thrust bordering the Lower Himalayas against the Sub-Himalayas. AUDEN (1937), and HEIM and GANSSER (1939) have studied this thrust on several traverses in the central and eastern part of the Kumaon Himalayas, and it is in this region that we will discuss the most salient items. The Main Central Thrust is well outlined in the Kali River gorge along the Nepalese frontier and again along the Goriganga and Pindar Rivers more to the west. Just east of the upper Ganges, the Alaknanda River, the thrust is less clearly defined, since underlying metamorphic rocks resulting from an upwards increase of metamorphism in the quartzite section of the Tejam belt are not unlike the overthrust masses, and the latter are complicated by some secondary imbrications (Kuari Pass, Fig. 55).

Along most contacts, at or near the thrust, occur the widespread amphibolitic sills of gabbro-dioritic composition (Fig. 62). Similar basic horizons have already been noted in conjunction with the smaller and some of the larger thrust masses in the Lower Himalayas. In spite of being intercalated with the upper horizons of the underlying sedimentary sections, their presence invariably near the thrust contact is not without significance. How far the genetic relations are of an ophiolitic nature, as suggested by the writer (GANSSER, 1959), is still debatable.

Excellent outcrops of the main thrust mass can be studied in the deep gorge of the Kali River, forming the border with Nepal in the eastern part of the Kumaon Himalayas (refer section 1, Pl. III). After crossing the complicated folds of the calcareous Tejam section, the Central Main Thrust is met just north of Darchula. The thrust is here surprisingly flat, and overrides at about 10 degrees the more steeply dipping limestones and slates. Along the river, the quartzites are cut out, the gneisses being in direct contact with the calcareous section. Basic rocks are missing, but set in with the quartzites further to the west.

The thrust rocks begin with a uniform coarse biotite-alkali-feldspar gneiss with rare plagioclase. The general aspect is that of a granitic gneiss. Upwards it grades, concomitant with the occurrence of muscovite and an increase in acidic plagioclase, into a muscovite-biotite augen gneiss, conspicuous by the amethyst colour of the large quartz grains. By an increase in schistosity, the feldspars are broken and sheared, while the amethysts remain as large rounded grains, suggesting a sheared quartz porphyry. The rounded amethysts of this striking rock type show characteristic Bömsche lamellae with a strong undulatory extinction.

After a thin horizon of biotite schists with intercalated biotite amphibolite, follows a new zone of biotite-granite gneisses, this time with less frequent alkali feldspars and a predominance of acid plagioclases. They are overlain by biotite-sericite schists with an intercalated large lense of a most extraordinary biotite-alkali-feldspar-porphyroblastic gneiss with bluish grey orthoclases of 15 cm length and 8 cm width. The orthoclase is bordered by beautifully developed myrmekitic reaction zones of the oligoclase-andesine. Upwards, the metamorphism seems to decrease and a conspicuous white quartzite with a coarse biotite amphibolite forms the base of the *sedimentary section of Sirdang* (Fig. 62).

This is characterized by a thick section of dark grey phyllitic slates with thin marble intercalations. The lime-free slates are graphitic and contain small scales of biotite with sericite. In the upper part muscovite-bearing calcium marbles are intercalated. Following on an amphibolite, thick snow-white sericitic quartzites form the base of the next higher crystalline thrust. A thin amphibolite is intercalated at the thrust plane. This thrust, with a northwards dip of 45° is considerably steeper than the lower thrust. We have seen that by the intercalation of the Sirdang sedimentary section the main thrust mass along the Kali River has been divided into a lower and an upper crystalline thrust, which, in spite of a most regular northerly dip, is of a much more complex composition than the lower thrust mass. The Sirdang sedimentary zone extends eastwards into Nepal, and the northern thrust can be connected with the main Katmandu thrust of HAGEN. No equivalent of the lower thrust mass is recognizable in western Nepal. Westwards, the Sirdang zone may be connected to the northern Tejam zone and the lower thrust mass

actually pinches out in the Goriganga. This interpretation is shown on the general geological and tectonic map. The front of the crystalline thrust sheet north of Tejam at Girgaon runs in an ENE direction into the Goriganga Valley where it is well exposed at Mansiari. Its continuation from here into the thrust north of Sirdang (Sirdang thrust) seems much more plausible than its connection with the southern thrust mass north of Darchula. The general metamorphism of the sedimentary Sirdang zone is higher than the average northern Tejam zone, and could be compared to the increased metamorphism in the uppermost quartzitic sections below the crystalline thrust masses (Fig. 63).

The next crystalline thrust, above Sirdang (sect. 1, Pl. III), begins with a sharp contact above the amphibolites, again with garnet-bearing biotite-muscovite gneisses similar to the ones met just below the biotite schists lying under the Sirdang zone (Figs. 62, 63). A difference, however, is the garnet content and the irregular composition caused by an incipient mobilization of the gneisses, leading to migmatitic rocks with some granitic bands of a peculiar "greisen"-like aspect, with predominant quartz, acid plagioclase and large muscovite flakes. More generally, the mobilization leads to aplitic tourmaline granites, some with radial tourmaline aggregates, which already show an intrusive nature. As we will see later, this type of tourmaline-aplite granite belongs to the youngest and post-orogenic "intrusive" rock type of the Himalayas. The general aspect of the two-mica garnet gneiss with its irregular incipient mobilization resembles the Darjeeling gneisses of the eastern Himalayas where they are very widely distributed.

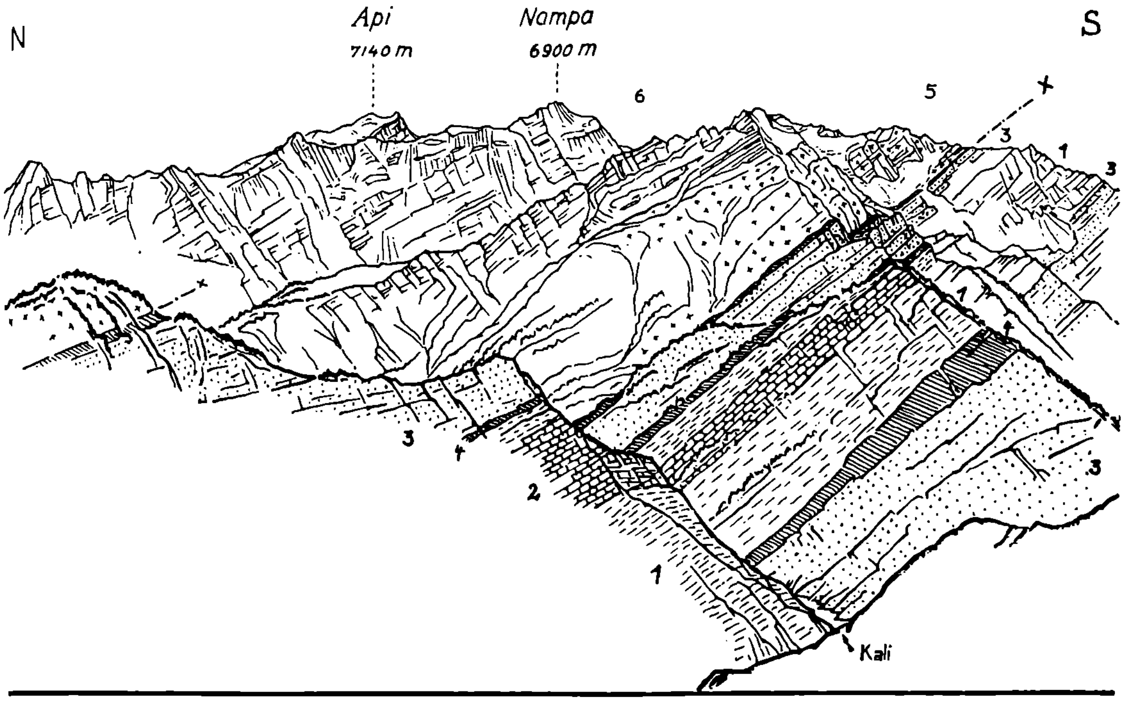


Fig. 62 *The sedimentary Sirdang zone with the northern branch of the Main Central Thrust.* View eastwards towards the Api-Nampa group. Kali River gorge, Kumaon Himalayas; after A. GANSSER (1959)

1 biotite phyllites, partly graphitic and calcareous } Sirdang zone
2 white sericitic marble }
3 quartzites
4 dioritic amphibolites
5 biotite muscovite gneisses
6 lime-silicate and quartzite zone, followed by Budhi and Garbyang schists
x Main Central Thrust

With an average NNE dip of about 50° dark garnetiferous biotite-psammite gneisses continue the sequence. They form the base of a multitude of intercalated rock types of various composition and origin. Staurolite-garnet-biotite phyllites, with perfect idiomorphic garnets are frequent. The garnets are interesting for their inclusions; their centres are rich in small inclusions of quartz and magnetite and they are bordered by a marked

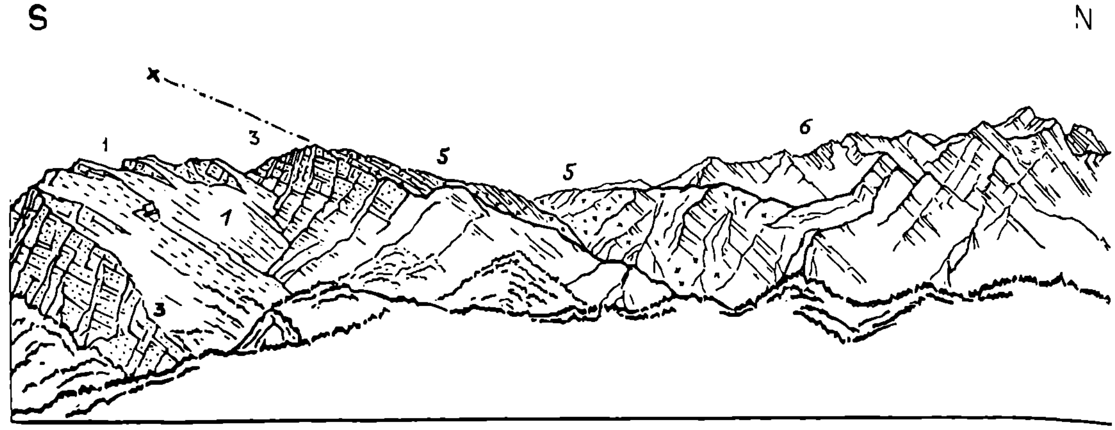


Fig. 63 *Main Central Thrust over Sirdang zone,* view to the W. Kali River gorge, Kumaon Himalayas; after A. GANSSER. For legend see fig. 62

rim of large quartz inclusions without ore and an outer rim of fine magnetite drops without quartz (Ph. 6). Between kyanite and biotite in kyanite-biotite schists one observes interesting reaction rims of quartz (Ph. 7). With the psammite gneisses and the phyllites occur thin amphibolites and larger layers of garnetiferous muscovite-biotite-alkali-feldspar gneisses, where the alkali feldspars are predominantly anorthoclases. Gradually, within the psammite gneisses appear the first thin horizons of *lime silicates*, rich in small red garnets, zoisite and some calcite. They are followed by a thick sequence of sericite quartzites, notable for large (up to 8 cm long) kyanites on the sericitic bedding planes of the quartzites together with garnets and black tourmalines. Within these quartzites, which in their upper part show tight folding (Ph. 8), occur the first larger *pegmatite dykes*. With a rather sharp border follow again large augen gneisses with feldspar augen up to 10 cm, which in turn grade into the previously mentioned and widespread biotite-psammite gneisses. Here the pegmatites increase until a dense network of dyles is met. They consist of tourmaline pegmatite, poor in mica, with large orthoclases and some acid oligoclase. Associated with the pegmatites are dykes and smaller stocks of a fine-grained muscovite granite and very characteristic muscovite-tourmaline-aplite granites. These very young intrusions increase eastwards and are well exposed in the steep southwest wall of the Api Mountain group in NW Nepal (Fig. 64).

Together with the increase in dyke intrusions goes an increase of intercalations of lime silicates

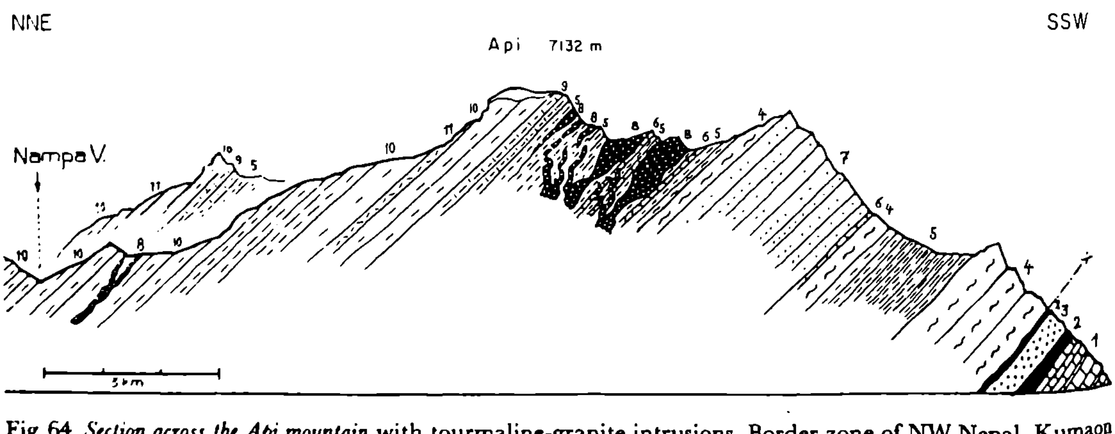


Fig. 64 *Section across the Api mountain* with tourmaline-granite intrusions. Border zone of NW Nepal, Kumaon Himalayas; after HEIM and GANSSER (1939)

1 slates and marbles } Sirdang zone
2 amphibolites
3 quartzites
4 migmatitic gneiss
5 garnet schists
6 lime-silicate layers
7 kyanite quartzites
8 tourmaline aplitic granites
9 Budhi schist
10 Garbyang series (Pre Cambrian – Cambrian)
11 green schists in 10

within the well-stratified but finely subfolded biotite-psammite gneisses (Fig. 65). Some of the lime silicate marbles can be over 20 m thick and, with the pegmatites and granite intrusions, form one of the most complex metamorphic sections met in the various profiles and seem of a surprisingly constant development (Fig. 65 and sect. 1, Pl. III). The lime silicate horizons are mostly well banded and vary considerably in composition. From lime silicate gneisses we come to larger diopside calc-marbles and coarsely crystalline scapolite-bearing phlogopite marbles. Some intercalated plagioclases are of labradorite or even more basic type. Scapolite is often found along the contact of the through-cutting pegmatites and granites. Otherwise hardly any appreciable contact zone is present.

Northwards and upwards in the section, the dyke intrusions diminish. The marbles disappear and some bands of pure actinolite are intercalated in the biotite-psammite gneisses which already show an increase in elongated larger biotite porphyroblasts. With a decrease in metamorphism we enter a most conspicuous zone of biotite-porphyroblast schists where the biotites cross the stratification. They are well developed at Budhi, and have been called the *Budhi schists*. As we will see, they have a very widespread distribution as the top formation of the main metamorphic sequence. Though the decrease in metamorphism is in line with the decrease in the dyke intrusions, no direct relation between metamorphism and dyke intrusions exists, since the dykes of the pegmatites and the granites cut through pre-existing metamorphic rocks and show no visible trace of tectonic disturbance, while the surrounding rocks are intensely folded (Fig. 66). This picture remains constant in many other transverse sections of the Kumaon and even the eastern Himalayas. The regional metamorphism has a more deep-seated cause (heat front?), and the dyke intrusions are a possible follow-up, resulting from a deeper granitic body (Pl. II A).

A characteristic feature of the *Budhi porphyroblastic schists* are the large transverse biotites with sieve-like quartz inclusions. The latter were originally parallel to the schistosity, but have been rotated with the biotite into a transverse position by late orogenic movements (Ph. 9). Quartz has filled the voids left by the rotated biotites. The Bhudi schists form the transition from the highly metamorphic rocks to the only slightly metamorphic sections of the thick late Precambrian to early Cambrian sediments—the Martoli, Ralam and Garbyang formations.

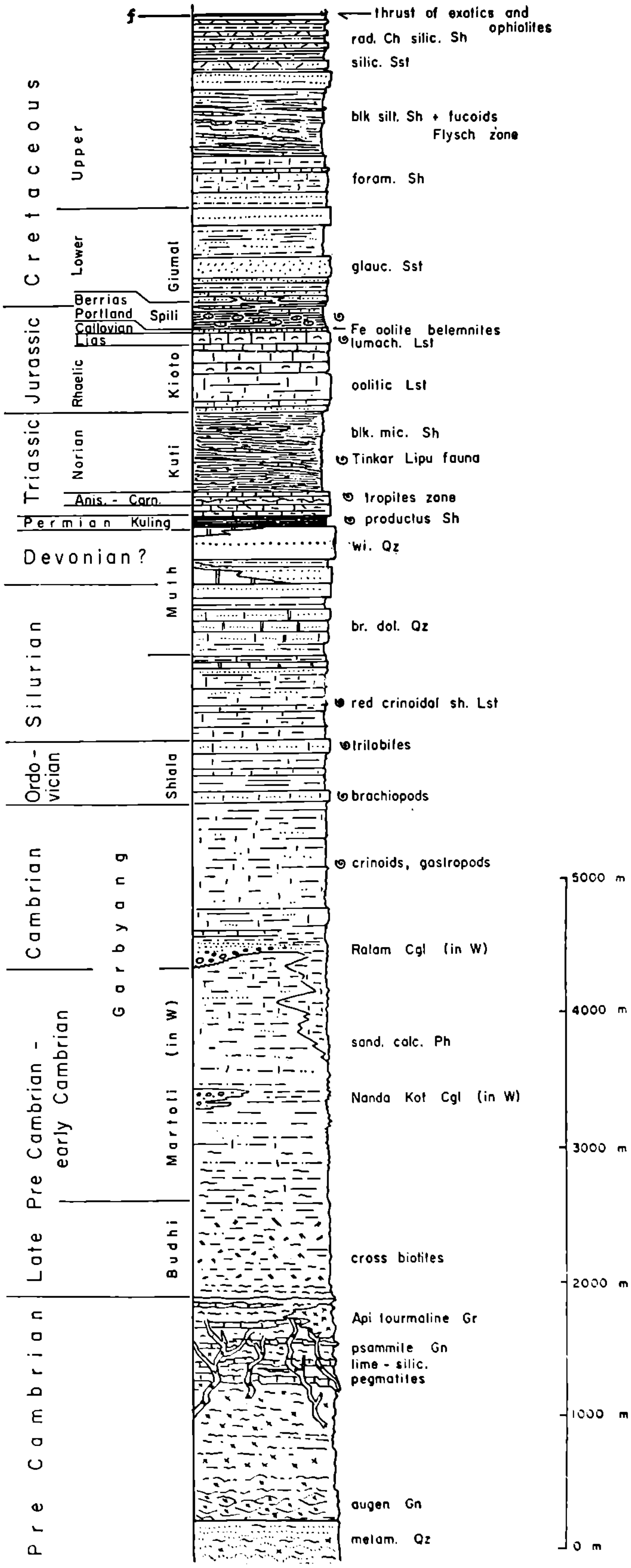


Fig. 65 *Stratigraphy of the eastern Higher and Tibetan (Tethys) Kumaon Himalayas;* compiled from HEIM and GANSSER (1939) (excluding the exotic thrust masses)

The crystalline base of the Higher Himalayas as described above is met in several other cross sections, and most of the more important subdivisions can be recognized again.

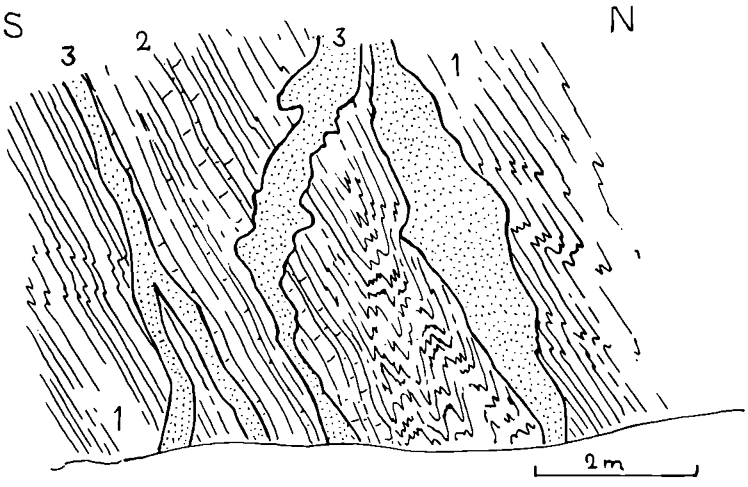


Fig. 66 *Detail of lime-silicate and psammite gneisses with pegmatitic and granitic dyke intrusions.* Note minute folding Kali Gorge, Kumaon Himalayas; after A. GANSSER (1939)

1 biotite-psammite-gneiss, often intensely folded
2 lime-silicate layers
3 pegmatite and tourmaline granite dykes

Eighty kilometres west of the Kali section the author studied the metamorphic rocks along the *Pindar River* and over the Pindar Glacier and Triall Pass (section 2, Pl. III). The basal large biotite-muscovite augen gneisses are met again, and so are the thick sericitic quartzites. Most characteristic here, too, are the psammite gneisses with the same lime silicates and the profusion of pegmatite and granite-aplite dykes (Fig. 67). Every detail of the Kali section is repeated with surprising precision, including the outstanding Bhudi schists which here form also the base of the huge sedimentary pile of the Martoli formation—the main rock of the 7820 m high Nanda Devi.

Along the *Alaknanda River* (section 4, Pl. III), south of the holy place of Badrinath, the crystalline section is again the same as in the eastern

Phot. 9 *Sieve-like biotite porphyroblasts in the Budhi schists.* The inclusions in the biotite are mostly quartz. Some of the porphyroblasts are rotated. Enl. 35×

Phot. 10 *The Badrinath Peak* (7140 m), built of Badrinath granite, seen from the E (phot. A. Gansser)

Phot. 11 *Walls of Badrinath granite with intercalated muscovite gneisses.* Satopanth Valley (phot. A. Gansser)

Phot. 12 *The Shivling* (lower Gangotri Glacier), a Badrinath granite peak capped by black schists, which are covered by summit ice and snow (phot. A. Sutter)

Phot. 13 *Nanda Devi main (W) summit,* 7820 m, with synclinal Martoli phyllites and quartzites, seen from the Rishi Gorge (towards south-east) (phot. A. Heim)

Phot. 14 *Ralam conglomerate,* with quartzite pebbles in a reddish to greenish greywacke type matrix. Upper Gori Valley, above Milam (phot. A. Heim)

Phot. 15 *Ordovician sandy calc schists on Shiala Pass* (Shiala formation), dipping steeply to the north (phot. A. Heim)

Phot. 16 *The well-bedded Liassic Laptal limestones,* covering the Rhaetic Kioto limestones to the right and followed by Spiti shales to the left (Smooth valley). Laptal (phot. A. Heim)

Phot. 17 *The Kiogar Gorge cut into anticlinal Rhaetic Kioto limestones* near Laptal (phot. A. Heim)

Phot. 18 *The Kiogar Mountains seen from SW.* 1, 2, 3, folded lower to upper Giumal sandstones, 4, red and green calcaerous shales, 5 black Flysch with fucoids, b = basic igneous rocks with serpentine at S, topped by the white exotic limestones of the Kiogars. (Compare also Fig. 79) (phot. A. Heim)

Phot. 19 *Kiogar Nr. 1 peak* (5800 m) consisting of Trias limestone (1) and Jurassic oolitic shaly limestones (2) sitting on basic igneous rocks, well visible to the left (3), underlain by Flysch with exotic blocks and volcanics (4). f = main thrust above normal U. Cretaceous Flysch (5). Note strong solifluction. View to north (phot. A. Heim). (See also Fig. 79)

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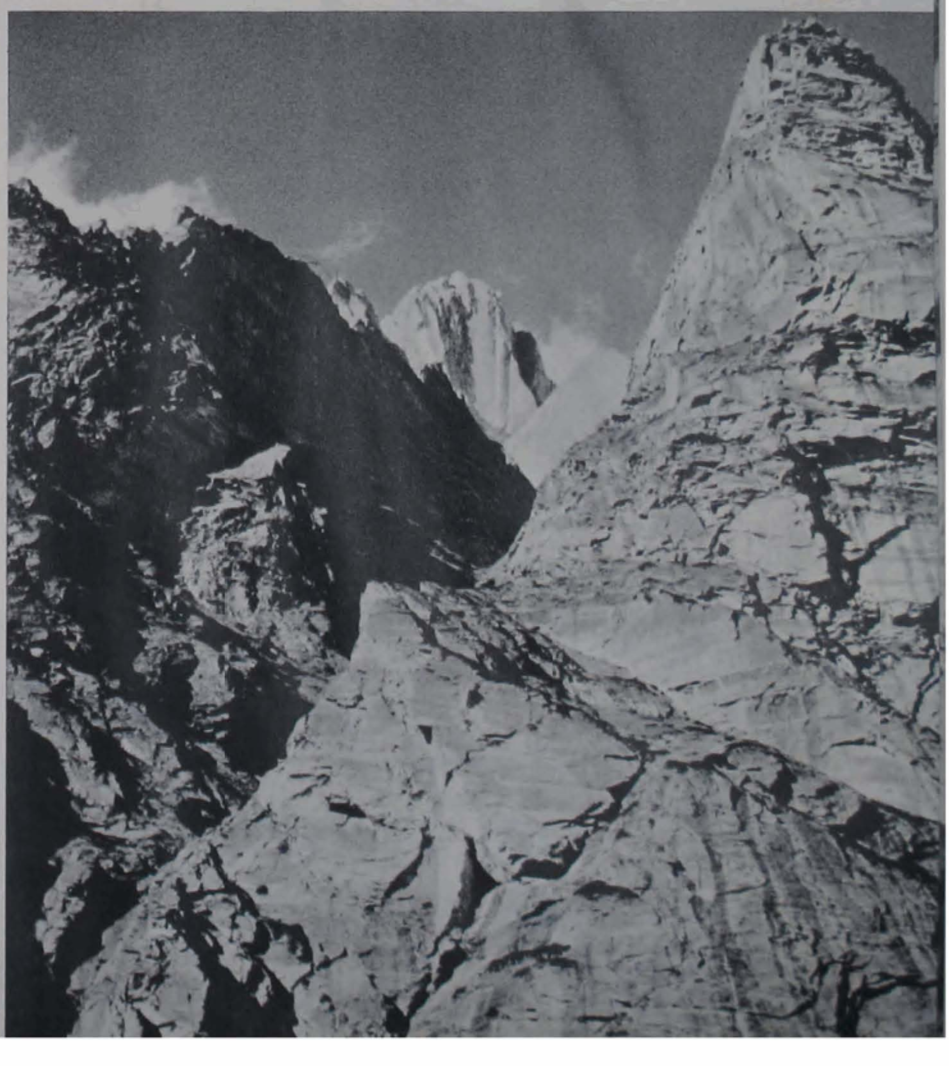

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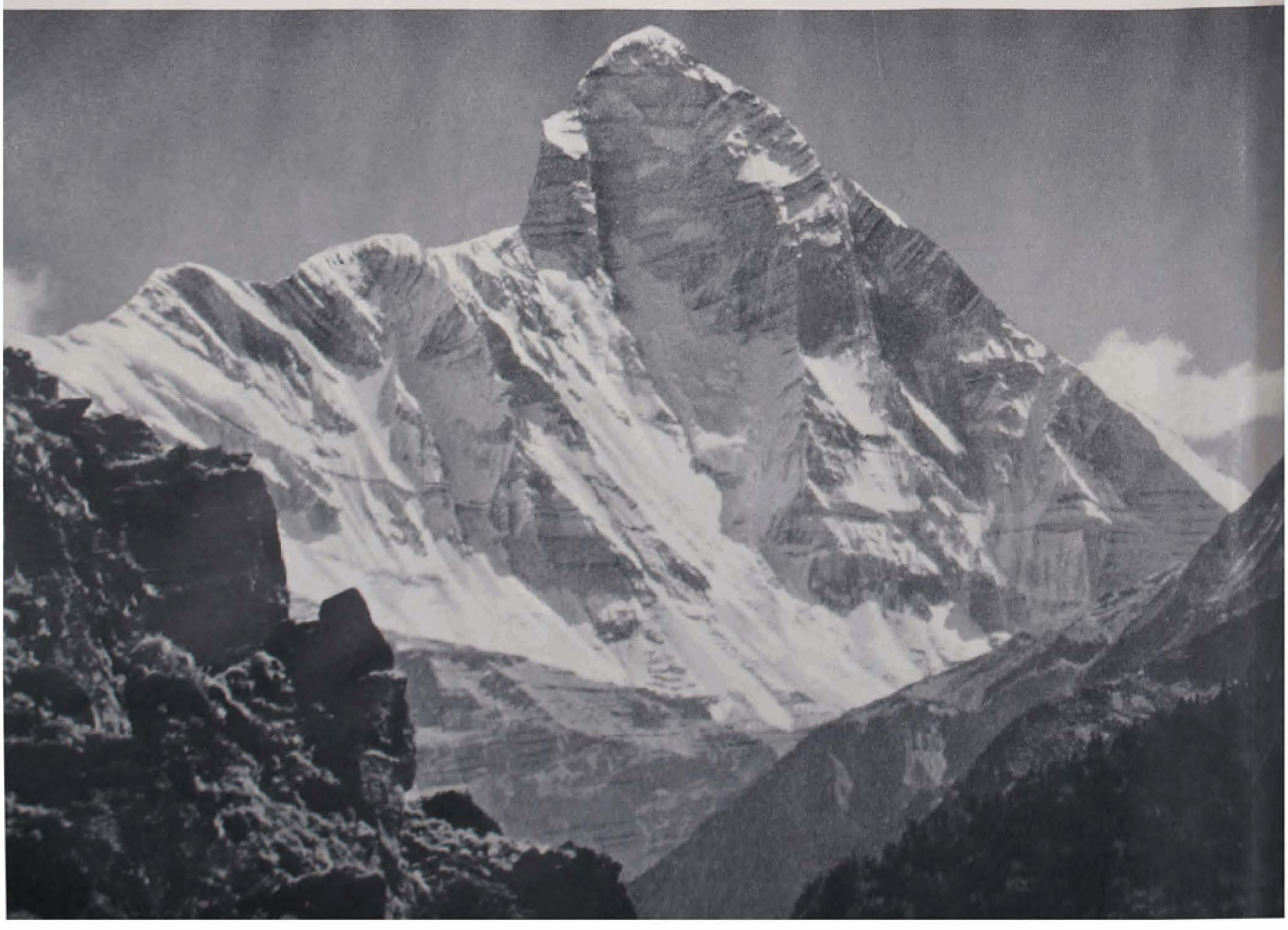

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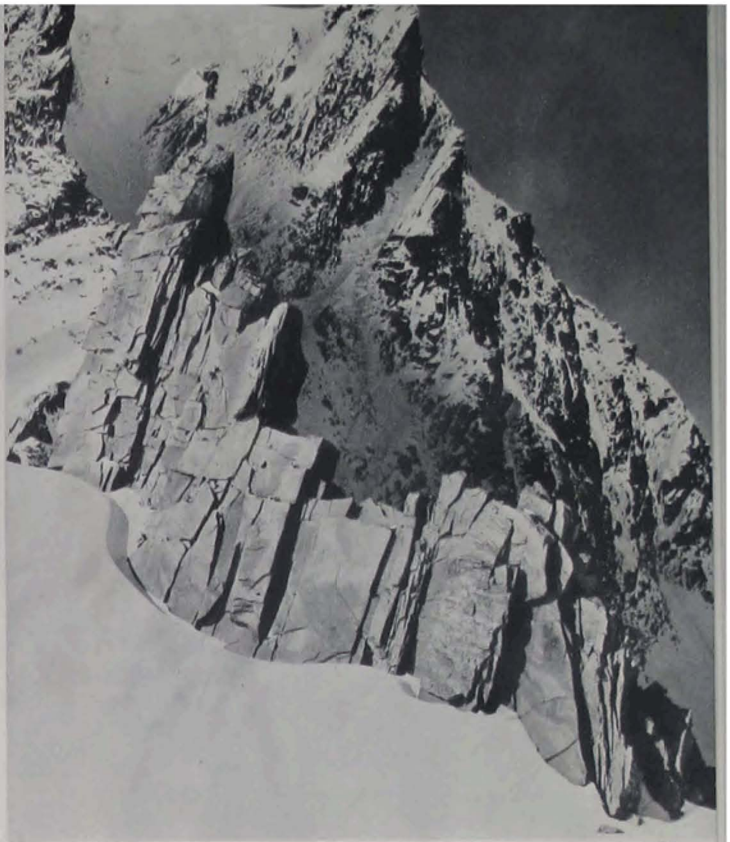

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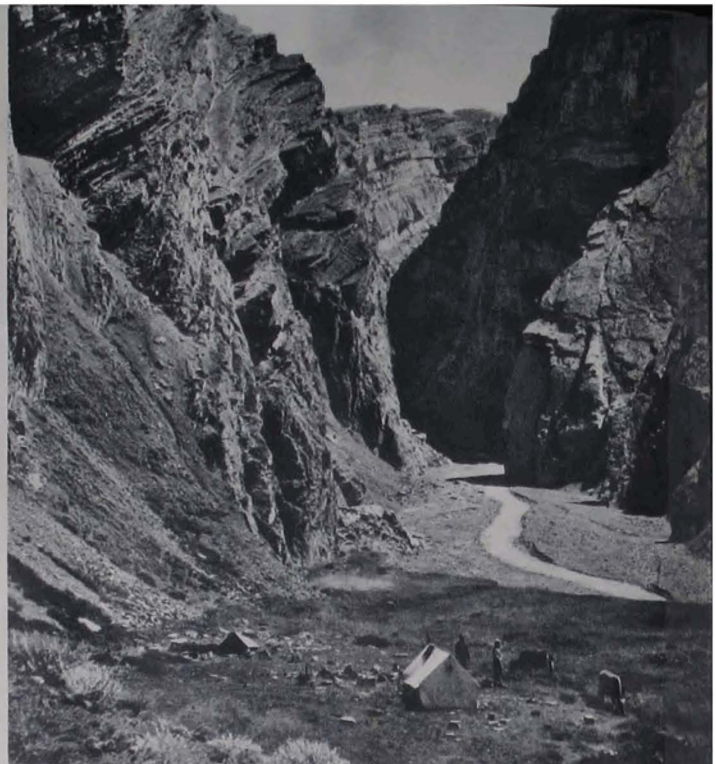


17

19

areas, with garnetiferous gneisses of the Darjeeling type but with a much larger development of quartzites (Fig. 68). AUDEN (1935) observed cross-bedding in the quartzites (his "granulitic

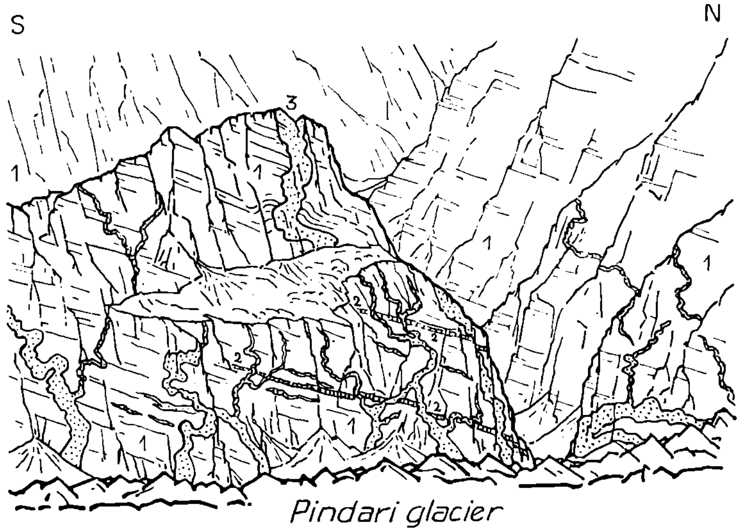


Fig. 67 *The lime-silicate zone with psammite gneisses and profuse pegmatite and granite dyke intrusions* at the Pindari glacier. Kumaon Himalayas; after A. GANSSER (1939)

1 biotite-psammite gneisses
2 lime-silicate layers
3 aplite, granite and pegmatite dykes

series") and he, too, arrives at a thickness of over 9000 m. This huge pile of quartzites seems normal considering that all along this section a dip of 45° is visible with hardly a change in strike and no indication of tectonic repetitions. Northwards the quartzites steepen to about 60° and are overlain by biotite gneisses with lime-silicate layers reminiscent of the sequence of the previously described sections. The only difference is the occurence of several garnet amphibolite horizons and the lack of younger pegmatite and granitic intrusions in this calcareous belt. Such intrusions are not lacking in the Alaknanda section but they occur further to the north, at the northern end of the lime-silicate sequence, where scapolite-diopside marbles pass into the young mass of the Badrinath granites.

Just south of Badrinath village the steepening lime-silicate and gneiss zone turns over and forms further north a flat anticline striking from southwest to the northeast, contrary to the general Himalayan strike direction. This anticline of gneisses is cut by pegmatites, granite dykes and by the large *Badrinath granite*, named after the Badrinath Peak (7140 m) (Ph. 10). The fresh granite is strikingly white and occurs as biotite-muscovite-tourmaline granite to granite-aplite. Tourmaline is always present. The biotite is often enclosed in larger muscovite flakes, and the orthoclases can form larger or smaller grains, resulting in coarser or finer granite types. As a whole the strikingly uniform granite is comparable to the

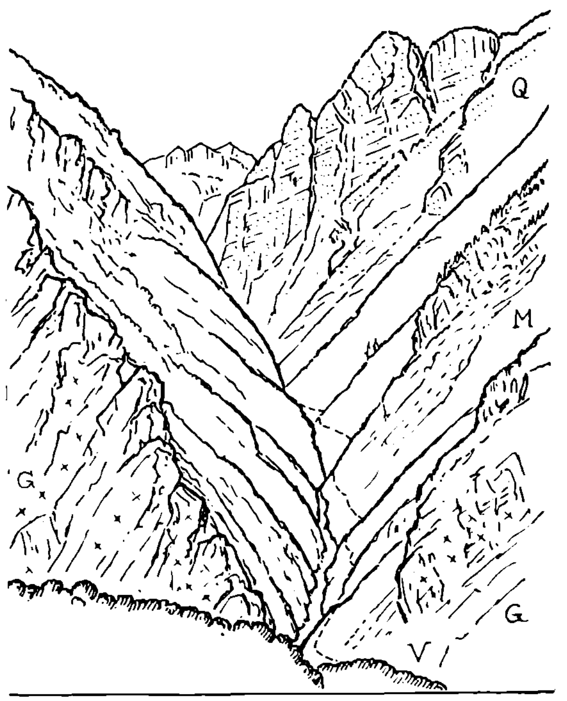


Fig. 68 *The gorge of the Alaknanda river* (Upper Ganges) cutting trough gneisses (G) garnet-mica schists (M) and quartzites (Q). Above Vishnuprayag (V). View towards N. Kumaon Himalayas; after HEIM (1939)

granite dykes and smaller stocks of the Api region along the Nepalese border. They represent the typical late to post-orogenic granite type of the Himalayas and can be observed over a very large extent. The constant composition is shown in two chemical analyses, one from the Api granite, the other representing the Badrinath granite. The results are quite similar for the two rock types, over a distance of 180 km (HEIM and GANSSER, 1939).

Api

		Niggli values	
SiO_2	71.90		
Al_2O_3	15.41		
Fe_2O_3	-		
FeO	0.78		
MgO	0.16	si	392
CaO	0.75	al	49.5
Na_2O	5.26	fm	5.0
K_2O	3.82	c	4.5
TiO_2	0.11	alk	41.0
P_2O_5	0.27	k	0.32
H_2O+	0.95	mg	0.27
H_2O-	-		
B_2O_3	0.64		
	100.05		

Badrinath

		Niggli values	
SiO_2	73.38		
Al_2O_3	14.56		
Fe_2O_3	-		
FeO	0.80		
MgO	0.11	si	426
CaO	0.81	al	50
Na_2O	4.27	fm	5
K_2O	4.17	c	5
TiO_2	0.08	alk	40
P_2O_5	0.19	k	0.39
H_2O+	1.57	mg	0.20
H_2O-	-		
B_2O_3	0.22 (in tourmaline)		
	100.16		

The Badrinath granite does not form a batholith, but rather a very large lens with intrusive contacts towards its underlying and overlying rocks. This lens dips gently to the northwest. The base is formed by the lime silicates and biotite-psammite gneisses of the Badrinath village region in which biotite and muscovite gneisses are intercalated (Ph. 11). The *lime silicates* are well exposed along the Satopanth Glacier, the actual source of the Ganges River, or Alaknanda as its upper course is called, where they often form lenses with diopsidic cores. Associated plagioclases show a most interesting zonal composition, with an andesitic rim and a core of bytownite to anorthite. Again frequent are coarse diopside phlogopite marbles, often with some hornblende. Pure-white marbles are equally present.

Quite different from the base of the Badrinath granite are the rocks of the hanging wall. These rocks are exposed in the region of the Bhagat Kharak Glacier, which drains from Badrinath

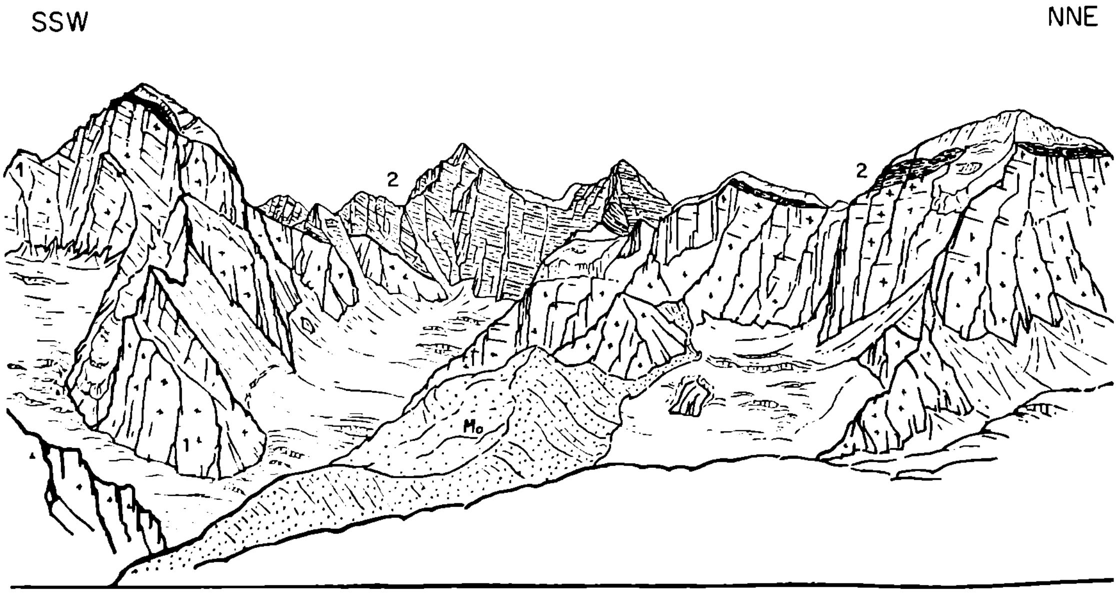


Fig. 69 *The head of Bhagat Kharak Glacier* with Badrinath granite (1) capped by black schists (2) (Mo Moraine), after A. GANSSER (1939)

Peak to the east. Here the granites are topped by strikingly flat black graphitic schists and/or graphitic biotite gneisses. They must have formed an old sedimentary cover, into which the young granite intruded. Similar schists were observed as lenticular xenoliths in the upper part of the granite. These black schists have a wide distribution, and are responsible for the black, flat-topped summits of the otherwise rather wild granite peaks (Fig. 69). They continue far towards the west into the Gangotri Glacier region, where they form the peculiar flat cover of the magnificent Shivling granite peak (Ph. 12).

Comparing the various crystalline sections of the Higher Kumaon Himalayas, we can note a normal sequence of *decreasing* metamorphism. This fact is particularly clear in the upper part of the crystalline thrust sections, which follows the lime-silicate zones and is clearly expressed by the porphyroblastic Budhi schists, grading into the Martoli-Garbyang formations. In all sections the part with lime silicates is characterized by conspicuous pegmatitic and granitic intrusions, culminating in the Badrinath-Kedernath region with large masses of very young tourmaline granites of a widespread and uniform composition.

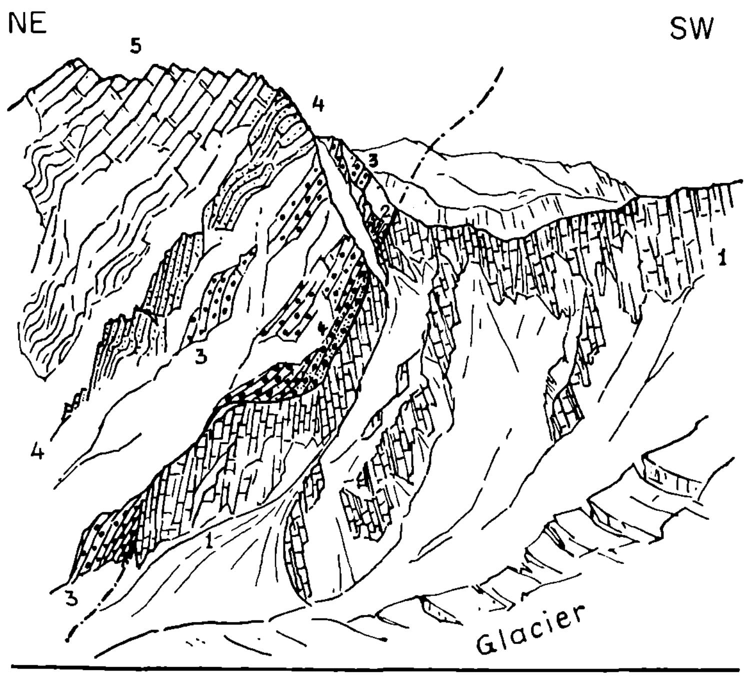


Fig. 70 *The Ralam conglomerate* NE of Ralam Pass (5500 m) transgressing on the Martoli series. Kumaon Himalayas; after A. Gansser (1939)

1 calcareous, quartzitic slates (Martoli formation)
2 quartzites with quartz pebbles }
3 coarse quartzitic conglomerate } Ralam conglomerate
4 coarse quartzite }
5 greenish to reddish quartzites and slates (Garbyang formation)

The Badrinath granite has been observed by Auden in the Gangotri group to the west (1949), and was found northwards in the Arwa Valley towards Mana Pass and Mana Peak, where tourmaline granite intruded older granite gneisses (Survey report, 1962). Along the abnormal strike of the Badrinath region (SW-NE) to the north the succeeding older sediments of the Martoli-Garbyang type become reduced, and the younger sediments follow on the Tibetan side of the watershed. The connection with the well-known Niti Pass in the northwest is still little-known. The dyke intrusions cut through the rather constantly northwards-dipping crystalline rocks and suggest an intrusion from a source vertically underneath. This does not apply to the lens-like intrusive mass of the Badrinath granite which looks more like a very large sill than a batholithic body. The regional metamorphism is not affected by the granitic intrusions, except very locally, and its normal upward decrease is in striking contrast to the upward increase of metamorphism of the thrust sheets of the Lower Himalayas, and, as we will see further in the east, in the Darjeeling region and Sikkim.

Lower sedimentary cover

The normal sedimentary cover of the crystalline thrust sheet of the Higher Himalayas consists everywhere in the eastern Kumaon Himalayas of thick monotonous argillaceous to calcareous fine-grained sediments (Fig. 65). They follow normally and conformably over the Budhi schists and form the highest mountains in this region (Api, 7140 m, Nanda Devi, 7820 m). In the Goriganga region (east of Nanda Devi) they are well exposed, and reach a thickness of over 4000 m. Named the *Martoli formation* after a village in the middle of their outcrop, they consist of fine-grained quartzite layers in a mass of more or less calcareous phyllites. Downwards they grade into the Budhi-type schists. Upwards they are transgressed by the Ralam conglomerate, exposed on both sides of the Ralam Pass. The Martoli phyllites and quartzites are only gently folded and form the wide syncline of the Nanda Devi double summit (Ph. 13). Within the Martoli quartzites and phyllites a coarse conglomerate must occur, which furnished the large blocks found by the author on the Lwanl Glacier, flowing from Nanda Kot. Well rounded to somewhat stretched oval pebbles of pinkish quartzite up to head size are embedded in a greenish quartzitic groundmass. Most probably, this conglomerate, called the *Nanda Kot conglomerate*, is only locally developed and must be distinguished from the younger Ralam conglomerate. The *Ralam conglomerate* consists of rounded quartzite pebbles up to head size in a black to reddish quartzitic to greywacke-like hard groundmass (Ph. 14, Fig. 70). Locally the conglomerate, which can be up to 100 m thick, transgresses unconformably onto the steeply north-dipping Martoli phyllites at an angle of about 30°. This unconformity, though local, is most significant since it would fall approximately into the base of the Cambrian, assuming a Cambrian age for the overlying Garbyang formations. It has so far not been observed outside the Kumaon Himalayas. The Ralam conglomerates are followed by grey-green and purplish fine quartzites and orange weathered dolomites, which grade into the thick section of very fine-grained yellowish phyllitic calcareous

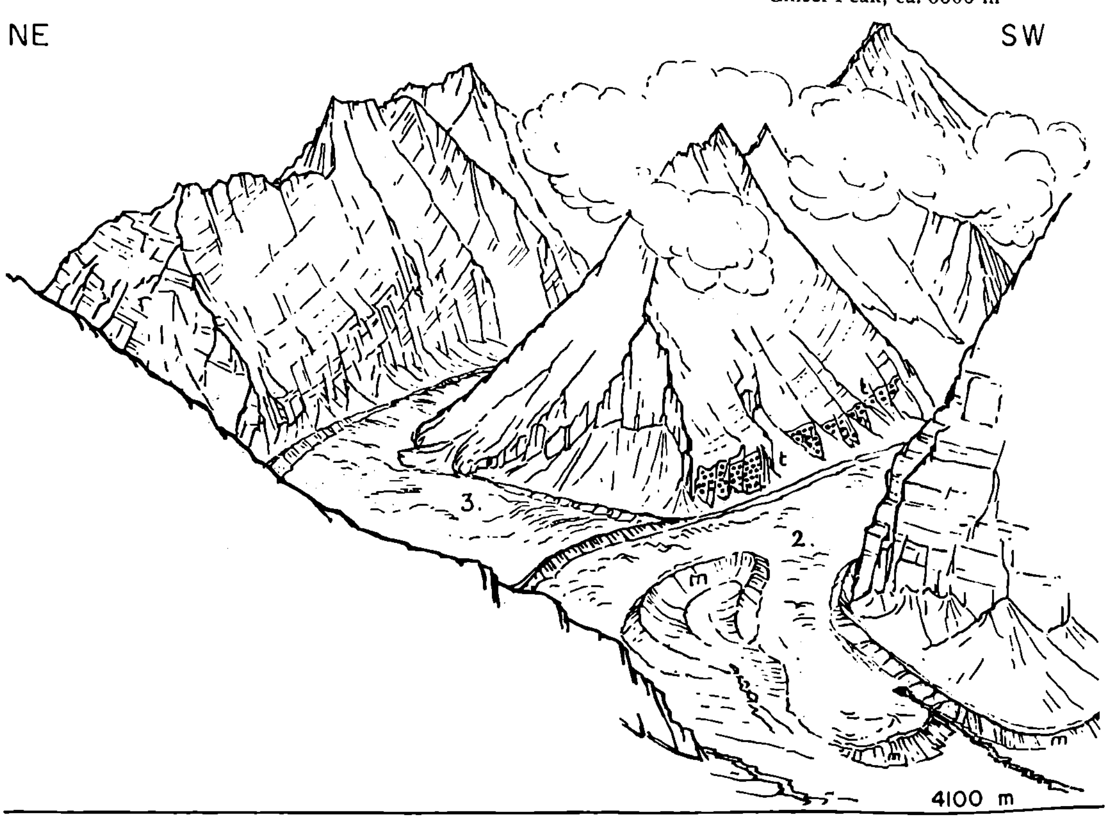


Fig. 71 *The thick Garbyang formation with tourmaline-aplite intrusions* (t) in the Nampa Valley (NW Nepal), border zone with NE Kumaon Himalayas; after A. Gansser (1939)

the north dipping Garbyang formation steepens to the south. Nampa Glacier (2) overriding Nampa glacier (3)

sandstones, calcareous argillaceous banded silts, calcareous quartzitic slates, and phyllites. A characteristic banding of the chloritic layers, probably of pyroclastic origin, can be noted throughout the section.

In the easternmost part of the Kumaon Higher Himalayas these calcareous shaly deposits develop from the Budhi schists by decreasing metamorphism, and the intervening Ralam conglomerates are missing. They were called *Garbyang formation* after the important mountain village of Garbyang. Here no clear division can be made between the Martoli and Garbyang formations, while in the more western area, where the Ralam conglomerates do exist, the Garbyang deposits overly the Martoli formation. This seems to indicate that the unconformity of the Ralam conglomerate is not very significant in spite of its certainly interesting stratigraphic position. Furthermore, the lithological difference between the Martoli and the Garbyang deposits is minor; the former are somewhat more phyllitic, the latter have a slightly higher lime content. Both formations are over 3000 m thick and surprisingly uniform. In the Martoli area the Martoli phyllites alone seem to exceed 4000 m and may even reach 5000 m. These enormous thicknesses of argillaceous calcareous sediments with only fine detrital material seem to reflect a peculiar mode of sedimentation. Similar thick sections of a very similar lithology, though less calcareous, are the Dalings in the eastern Himalayas which will be discussed in a later chapter. The Garbyang phyllites are normally overlain by fossiliferous Silurian. Within the Garbyang calcareous phyllites occur badly preserved large flat gastropods and some crinoid fragments (HEIM and GANSSER, 1939). This indicates that the Garbyangs are certainly not Precambrian, and that most probably a Cambrian age must be assigned to them. The lower part and particularly the Martoli phyllites might be late Precambrian. The fact that such uniform thick argillaceous sediments represent the Precambrian-Cambrian transition is surprisingly widespread, not only in the Himalayas but in many large mountain ranges, as for instance the Rocky Mountains (Belt argillites), the Andes (Quetame slates) and in the Elburz (Kahar slates). In many other mountains, such as the Alps, similar rocks have been metamorphosed and are no more recognizable, a situation similar to the alteration of the Daling slates into the Darjeeling gneisses.

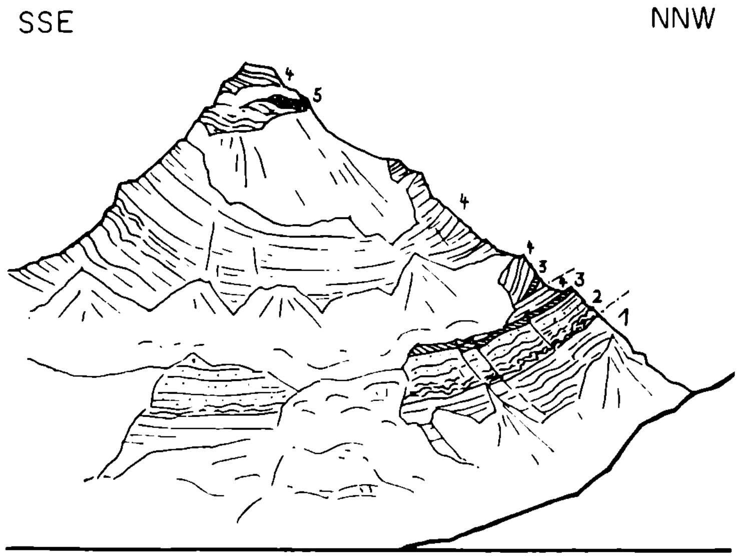


Fig. 72 *The synclinal structure of Nanda-Devi E* (7434 m) Kumaon Himalayas; after A. GANSSER (1939)

1 sericite quartzite and slates
2 white quartzites locally folded
3 dark slates?
4 sericite phyllites with yellowish carbonatic quartzites
(1–4 Martoli formation)
5 probable dyke of tourmaline-aplite

It is not yet clear whether deeper geosynclinal conditions governed the deposition of this enormous bulk of argillaceous sediments. The fact remains, however, that the following younger deposits reflect much more shallow marine conditions, as we will see in the Tethys-type sediments of the Tibetan Himalayas. It seems most likely that the geosynclinal argillaceous deposits of the late Precambrian and Cambrian are the

counterpart of the continental Vindhyans of the Peninsular area.

Only twice has the writer observed intrusions into the Martoli and Garbyang calcareous phyllites. In the Nampa Valley, north of the Api-Nampa range, the regionally north-dipping Lower Garbyang phyllites contain an intrusion of tourmaline aplite, not unlike the aplitic dykes south of Api Mountain (Fig. 71). Below the eastern summit of Nanda Devi, formed by a syncline of Martoli phyllites, the writer believed he could recognize, with field glasses, some dykes of tourmaline aplite. Their presence seemed to be confirmed by fragments of aplitic rocks found on the glacier at the foot of the high east wall (Fig. 72). Dykes were, however, not seen by the Polish expedition, when they climbed the Nanda Devi east peak in 1939 (ODELL, 1943).

TIBETAN OR TETHYS HIMALAYAS OF KUMAON

As already mentioned, a sharp division does not exist in the Kumaon Himalayas between the Higher Himalayas and the northern Tibetan or Tethys Himalayas. The sedimentary sequence is transitional from the Cambrian into younger deposits, and high mountains are still present in the northern ranges. Arbitrarily the division has been drawn north of the highest peaks such as Nanda Devi and Api, which are built of Garbyang and Martoli rocks respectively, of late Precambrian to Cambrian age. This division also coincides with a marked change in the tectonic style. Passing through the metamorphics from the Main Central Thrust into the first sediments of late Precambrian to Cambrian age, we have noted a strikingly uniform structure, actually a north-dipping enormous monocline. With the more differentiated Palaeozoic sediments a quite complicated tectonic begins, with several southwards-directed thrusts. This change in style is clearly visible on the enclosed general sections (1, 2, 3, 4 Pl. III and Fig. 73). The complicated structure of this part of the Tibetan Himalayas is the main difference between this area and the famous Spiti region. The stratigraphy up to the Cretaceous has changed little, but the

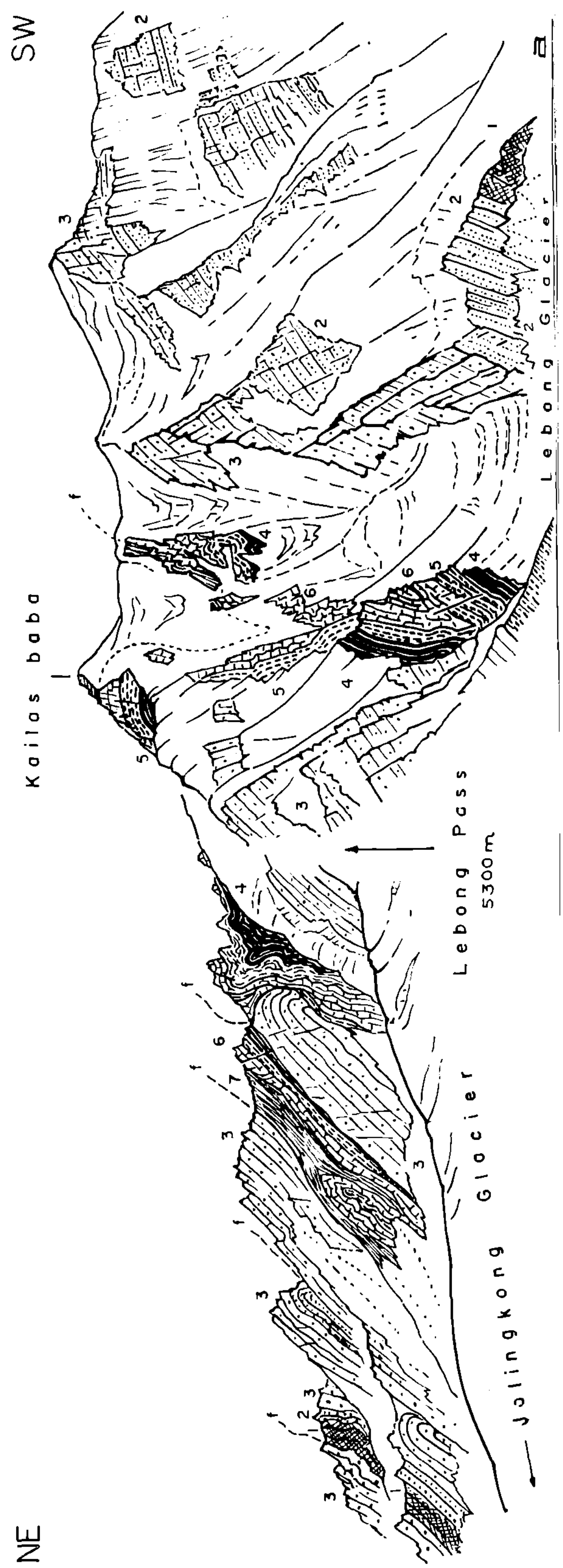


Fig. 73a *The change from regionally north-dipping Lower Paleozoic into disharmonic folds and "Schuppen" zones of the Upper Paleozoic and Lower Mesozoic* Lebong Pass region, Kumaon Himalayas; after A. GANSSER (1939)

1 red crinoidal shales (Silurian)
2 brown quartzites (Muth)
3 white quartzites (Muth)
4 black *Productus* shales (Permian)
5 Chocolate shales (Lower Trias)
6 Kalapani limestones (Middle Trias)
7 Kuti shales (Upper Trias)

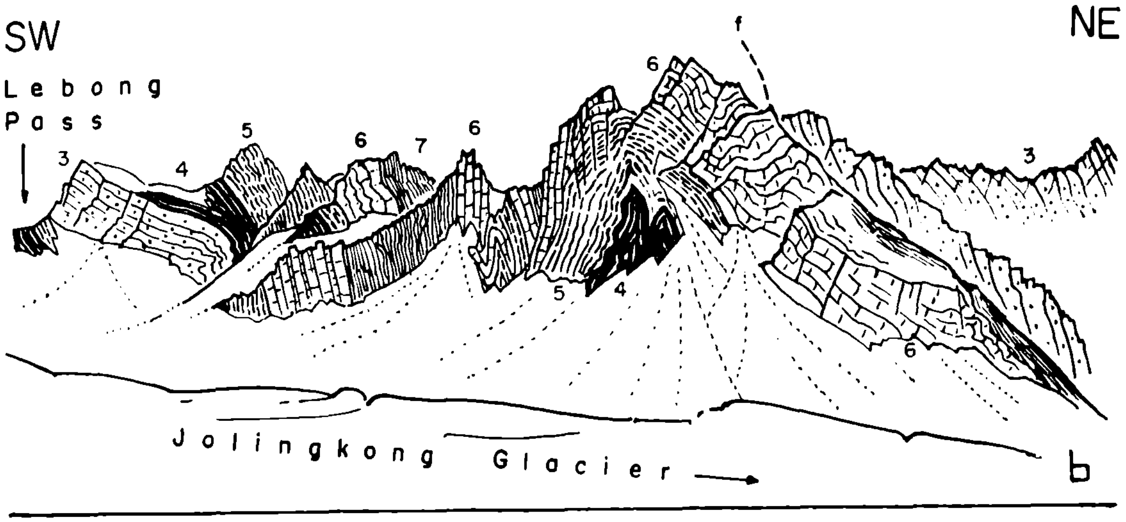


Fig. 73b *Same section as (a) on left side of Jolingkong glacier*

rather simple open Jura-type folds of the Spiti region have changed into a much more complex fold and thrust zone, which coincides with a narrowing of the northern sedimentary belt in front of the southwards-bulging exotic thrust mass. This does not mean that the tectonic reduction of the sedimentary belt is directly the cause of the exotic thrust mass, since the latter is most incompetent and the mechanism of its southwards movements is still a matter of differing opinions.

Normal sediments: Ordovician—Cretaceous

In the following descriptions of the northern sedimentary section we will point out some facts which differ from the Spiti area and deal principally with the tectonic aspect. For the rest we refer to the specially prepared stratigraphical column (Fig. 65).

Accepting a Cambrian age for the Garbyang formation, its equivalent in the Spiti area is richer in detrital deposits, less argillaceous and in general much thinner and less monotonous. The Ordovician quartz conglomerates and the following thick red quartzites have no equivalent in northern Kumaon. The Garbyang phyllites grade imperceptibly into variegated shales with sandy limestones and crinoidal breccias, well exposed at the Shiala Pass and therefore called the *Shiala formation* (Ph. 15). Some calcareous sandstones furnished an *Ordovician* fauna. Without any break, the Ordovician is followed by very characteristic red and white brecciated crinoidal limestones. They alternate with grey and green sandy shales and shaly limestones. In accordance with Spiti, the crinoidal limestones seem to represent the *Silurian*.

The *Muth quartzites* are well developed, with an impressive average thickness of 800 m. Dolomitic layers are intercalated in the lower part, and locally dolomite can replace even the white top quartzite. With a very sharp boundary, the quartzite is conformably overlain by the strikingly black *Productus* shales, which have furnished excellently preserved Upper Permian ammonites. In spite of the sharp but absolutely conformable contact, part of the Devonian and the whole Carboniferous is missing, and what is even more important, no trace of the Blaini-type tillites remains in this region. The striking contrast between the white Muth quartzites and the black *Productus* shales is an excellent marker assisting in unravelling the complex tectonics. Strong disharmonic folding between the competent quartzites and the incompetent shales is most characteristic (Figs. 78, 79) and the average 50 m thickness of the latter can increase tectonically to several times this figure.

The *Productus* shales are conformably followed by the brown limestones and slates of the *Lower Triassic*—the *Chocolate limestones* of GRIESBACH (1880). Here again we have the interesting fact that marine Upper Permian is conformably overlain by marine basal Triassic. In spite of the conformity, a small hiatus seems present in this part of the Kumaon Himalayas. The Upper *Productus* shales are followed by ferruginous limestones with *Ophiceras*, and it seems that the lowest *Otoceras* horizon is missing (Kuti region, Fig. 74). The question remains open, however, whether only the fossils are missing and the sedimentation is continuous, or whether a non-depositional gap exists. The details are similar in the Tinkar Lipu section of the northwestern corner of Nepal as well as in the Kuti and Kalapani region in northern Kumaon.

The Triassic as a whole is equally well developed and as rich in fossils as in the Spiti and Niti regions. The tectonics are, however, more severe, and normal sections are not frequent (Fig. 75).

The Kalapani limestone is rich in orange-coloured patches of ankerite, a very constant facies reaching into the Spiti area. Haematitic layers, rich in cephalopods, form the middle part. *The Tropites limestones* follow as a few-metre-thick band on top of the Kalapani limestone. This horizon merits special attention since DIENER described 155 species of ammonites from a 1 m thick section (1912). The rich fauna from Tinkar Lipu was collected from the same horizon (JEANNET, 1959). From the Kalapani region DIENER mentioned the curious fact, later confirmed from Tinkar Lipu by JEANNET, that Carnian and Norian ammonites are mixed within the same

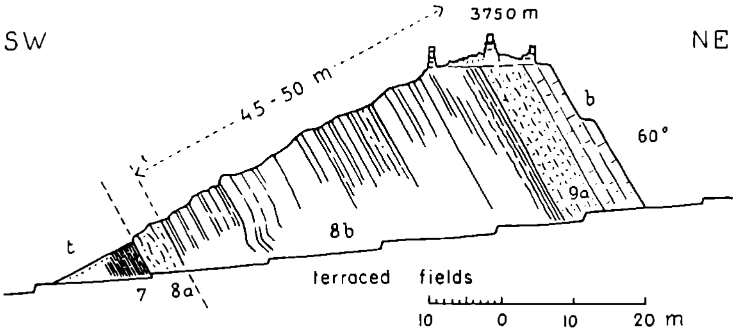


Fig. 74 *The contact of the Productus Shales with the Lower Triassic* at Kuti Castle Hill. Kuti region, Kumaon Himalayas; after HEIM and GANSSER (1939)

7 *Productus* Shales with sharp limit against 8 (Permian)
8a ferruginous limestones with *Ophiceras*
8b clay ironstone with slates
9a limestone lumachelle with some ammonites
9b compact limestones with crinoids and some ammonites
(Basal Triassic)

Excellent faunas were collected by HEIM and GANSSER from the Tinkar Lipu and the Kuti region and described by JEANNET (1958, 1959). The Trias can best be subdivided into five lithological units, which also correspond to stratigraphical subdivisions; the Chocolate shales (basal Trias), Kalapani limestones (Anisian-Ladinian), *Tropites* limestone (Carnian and Norian), the Kuti shales (Norian) and the Kioto limestone (part Norian, predominantly Rhaetic).

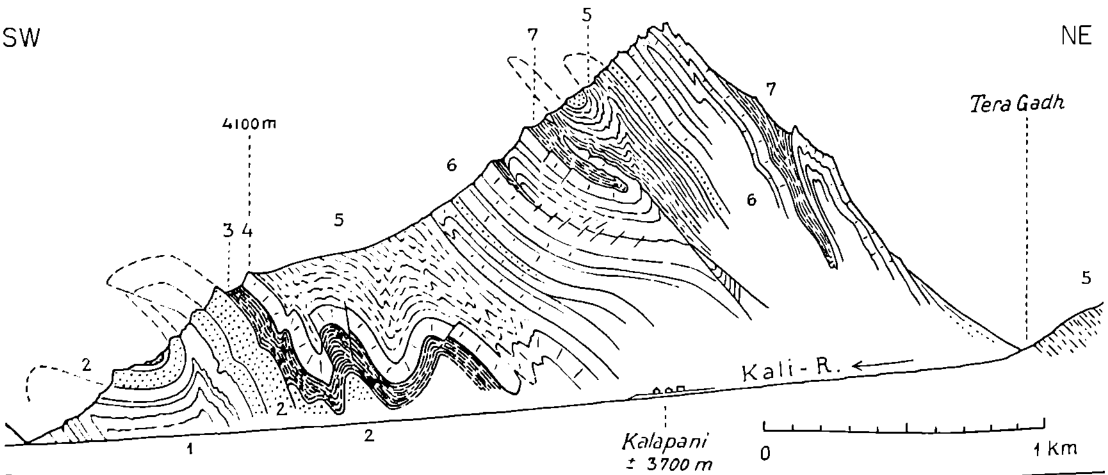


Fig. 75 *Section along the upper Kali River* at Kalapani. Kumaon Himalayas; after A. HEIM (1939)

1 dolomites with some quartzites (Silurian)
2 Muth quartzites (Silurian/Devonian)
3 *Productus* Shales (Permian)
4 Kalapani limestone (Muschelkalk)
5 Kuti shales (Upper Triassic)
6 limestones with quartzite horizon (U. Triassic-Rhaetic)
7 black shales, probably Spiti shales

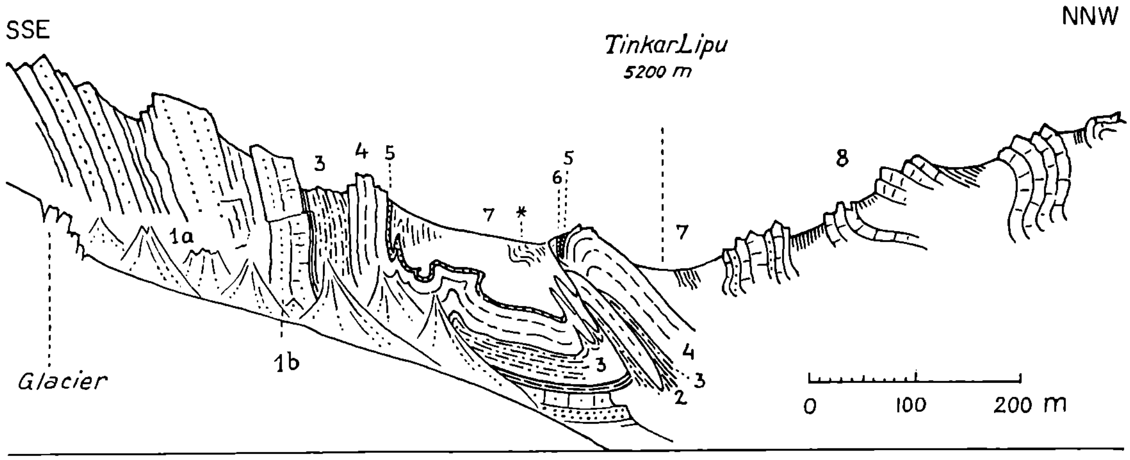


Fig. 76 *Section across the Tinkar Lipu* (NE Nepal Tibet border); after HEIM and GANSSER (1939)

1a Muth quartzites
1b Muth quartzites with dolomites
2 Productus Shales (only traces)
3 Chocolate shales
4 Kalapani limestones
5 sandy limestone containing mixed Carnian and Norian ammonites
6 foliated sandstone
7 Kuti shales with very rich Norian ammonite fauna
8 Kioto limestones with shales, partly oolitic

horizon. The fossils show no sign of redeposition, nor does the limestone contain any phosphatic nodules, comparable to Alpine stratigraphical condensations (HEIM, 1934). Furthermore, no intermediate forms were observed, but only true Norian or Carnian species were found. Stratigraphical condensation seems not the right solution for this still-unsettled problem.

The Kuti shales are well developed on the Tinkar Lipu, a 5200 m pass leading from northwestern Nepal into Tibet (Fig. 76). Normally they consist of 300-500 m of black micaceous shales. On Tinkar Lipu, black calcareous slabs are intercalated, in which the writer discovered the Norian fauna described by JEANNET (1958, 1959). This rich cephalopod fauna contains many new species. Upwards the Kuti shales pass over a thin quartzite horizon into the 200-600 m thick bluish limestones, which in this lower part are oolitic. They can be correlated with the *Rhaetic Kioto limestones* of Spiti, which may contain at its base some Norian horizons.

In some areas the Kioto limestone facies may reach into the Liassic and possibly even into the Dogger, covered by the Spiti shales as is the case in the Spiti region. In the northern and northeastern Kumaon, HEIM and GANSSER were able to distinguish the Liassic in the form of their *Laptal beds* consisting of several lumachelle horizons alternating with thin-bedded limestones (Ph. 16). They are followed by *Callovian ferruginous oolites*, discovered by DIENER in 1895. Laptal beds and Callovian oolites normally form a continuous section above the Kioto limestones, or rather a continuation of the Kioto limestones (Ph. 17). They are not everywhere developed,

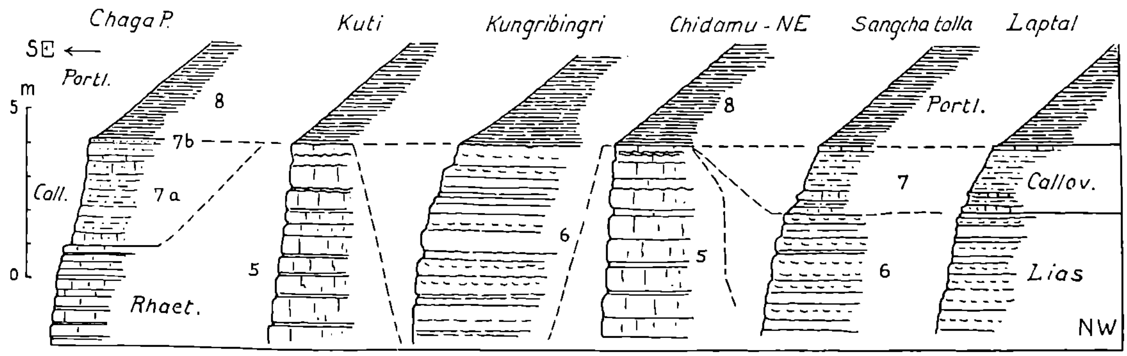


Fig. 77 *Correlation of the Triassic-Jurassic section*, Kumaon Himalayas; after HEIM and GANSSER (1939)

5 Upper Kioto limestones
6 Laptal lumachelle
7 ferruginous oolites, Callovian
8 lower Spiti shales

and when missing the very widespread Spiti shales follow directly with a sharp discontinuity over the Kioto limestone (Fig. 77).

The *Spiti shales* of the Kumaon Himalayas are typically developed and do not differ from those of the famous Spiti locality. The black lustrous shales with the characteristic black fossiliferous concretions can reach a thickness of 100 m, but owing to their very incompetent nature they may locally show structural thickening. Tectonic disturbances, solifluction and the washed-out concretions with ammonites are the main reason that no detailed stratigraphical section can as yet be given. The upper part of the Spiti shales contains some flaggy limestones (Kungribingri Pass) and they may actually reach into the Valanginian. ARKELL (1956) places the Upper Spiti shales into Upper Tithonian, Berriasian and Valanginian.

The contact of the Spiti shales with the overlying arenaceous Cretaceous, the *Giumal sandstones*, is gradual. In the uppermost shales we find intercalations of calcareous, glauconitic sandstones, grading into the massive glauconitic *Lower Giumal sandstone*. This sandstone is followed by greenish reddish and black silty shales overlain by a second thick sandstone body—the *Upper Giumal sandstone*. The total thickness of the Giumal sandstone section exceeds 500 m. Without any sharp break, the Giumal sandstone is covered by a thick section of red to purplish marly shales and marly dense limestones with a few pelagic foraminifera, black silty shales, slates with thin partly siliceous sandstones, and limestone flags with fucoids. The top is formed by characteristic red and green fine siliceous sandstones, red radiolarites and siliceous shales. They represent the highest section in the Northern Kumaon Himalayas and are overthrust by the exotic thrust sheet with its basic igneous rocks. Some parts of the Giumal sandstone, but particularly the higher argillaceous silty section, are strikingly similar to some Alpine Flysch deposits. It is not unlike some of the previously mentioned Indus Flysch sections. The presence of Flysch-like deposits in this northern part of the Himalayan range is of special interest, since Flysch sediments are normally missing along the Lower Himalayan front and the Siwalik Molasse. This fact distinguishes the Himalayas from the Alps with their very widespread Flysch belts.

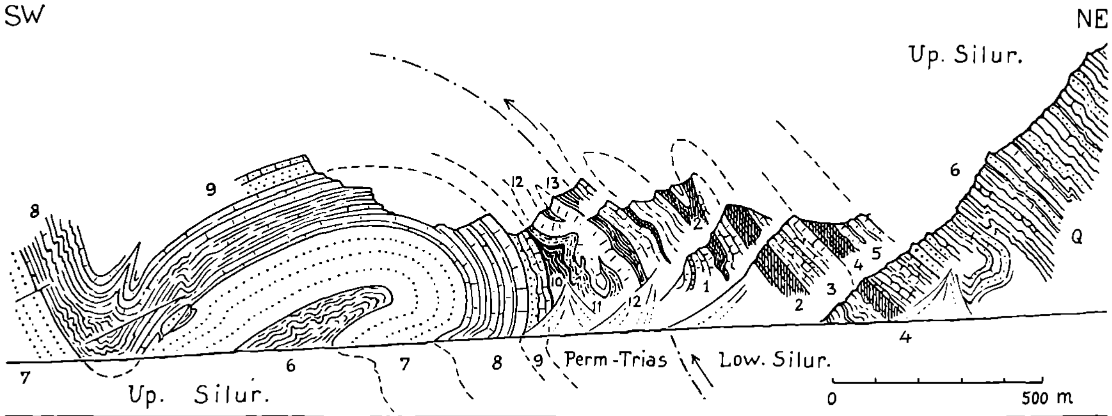


Fig. 78 *Disharmonic folding and thrusting in the Upper Kali region.* Kumaon Himalayas; after HEIM and GANSSER (1939)

1 crinoidal limestones, 2 variegated slaty marls, 3 calcareous sandstones, 4 variegated shales, 5 well-bedded limestones — Silurian
6 thin-bedded quartzites with dolomites and limestone bands — Muth quartzite section
7 massive white quartzites, 8 well-bedded dolomites, 9 white quartzites — Muth quartzite section
10 *Productus* Shales — (Permian)
11 Chocolate series, 12 Kalapani limestone, 13 Kuti shales — Triassic

Nothing is known so far of the distribution of this North Himalayan Flysch basin, the origin of its detrital material or the direction of deposition. As we will see, Flysch-like sediments are also involved in the exotic thrust masses and can be followed far into Tibet. Without further studies in this most interesting area many of its problems remain unsolved.

We have already drawn attention to the complicated, mostly disharmonic folding and thrusting in this northern sedimentary belt. Most of the thrusts develop from shale sections, such as the *Productus* shales and the Kuti shales. Generally, the quartzitic Silurian is thrust over Permian, Triassic or even Spiti shales (Fig. 78, 79 and

sections 1 and 3, Pl. III). All thrusts dip clearly to the north and the general direction of the assymetric folds is, with a few exceptions (Fig. 78), southwards. The detailed as well as the regional tectonic picture suggests a general superficial movement from the north to the south, in line with the main movement of the Main Central Thrust. This fact merits special emphasis, since it does not conform with some of BORDET's suggestions of northwards-directed gravity tectonics of the Tethys Himalayas related to the young uplift of the Higher Himalayan range (BORDET, 1961).

not including similar outcrops south of the Kailas Range over 100 km to the ENE.

The Flysch of the Tibetan Himalayas of Kumaon, mentioned in the previous section, forms N-S-directed structures in the Kiogar region. In the deeper sections, competent Triassic limestones form Jura-type anticlines, but with the overlying Spiti shales disharmonic folding sets in. Some of the Flysch folds, above the again rather competent Giumal sandstones of Lower Cretaceous age, show independent though still N-S striking structures. They definitely plunge in a northerly direction, below the large thrust

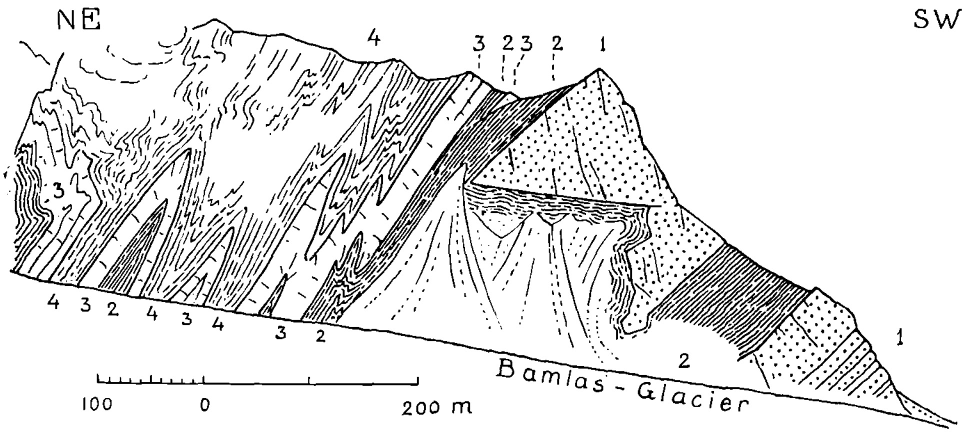


Fig. 79 *Disharmonic folding in Upper Goriganga* above Milam, Kumaon Himalayas; after HEIM and GANSSER (1939)

1 massive, fractured Muth quartzites
2 *Productus* shales
3 Kalapani limestones
4 Kuti shales

Exotic region of the Tibetan Kumaon Himalayas

More than 70 years ago, GRIESBACH (1891, 1893) and DIENER (1898) discovered exotic blocks along the Indo-Tibetan border in the Kiogar-Chitichun region (30 km N of Milam). A few years later VON KRAFT mapped the same region in more detail and came to the peculiar conclusion that the chaotic blocks resulted from huge volcanic explosions in Tibet. DIENER (1898) noted the exotic blocks "in their occurrence amidst much younger sediments, and without apparent stratigraphical connection with the latter, which makes the structure of the Chitichun area one of the most intricate and most remarkable in the Central Himalayas". This statement is still true, and after the recognition of similar exotic block regions related to ophiolitic belts in many other places (GANSSER, 1959), is of world-wide importance. Through the investigations of the author in 1936 in the adjoining southern Tibet, the known area of the exotic blocks of Kiogar-Chitichun was extended to more than 5000 sq. km, mass of the exotic Kiogars (Fig. 80, Ph. 18 and Sect. 2, Pl. III). The youngest Flysch-type sediments preserved locally below the thrust mass are siliceous black, red and green shales and red radiolarites of Upper Cretaceous age. The Flysch masses of the Kiogar region do not represent a normal section. The presence of exotic blocks within the Flysch, some of which are related to thrusts connected to larger exotic masses, suggest tectonic complications. Unfortunately, solifluction is widespread in the Kiogar Flysch zone, so that normal contacts are rare or that many of the exotic blocks have slipped and are no longer in their original position.

In the Kiogar region we can distinguish three main horizons of exotic blocks:

1. Exotic blocks in the Flysch.
2. Exotic blocks in the basic vulcanites.
3. The Kiogar exotic mass.

1. *Exotic blocks in the Flysch* are seen only as erratics; many may not be in their normal position because of the strong solifluction. In some instances, however, the contacts of such

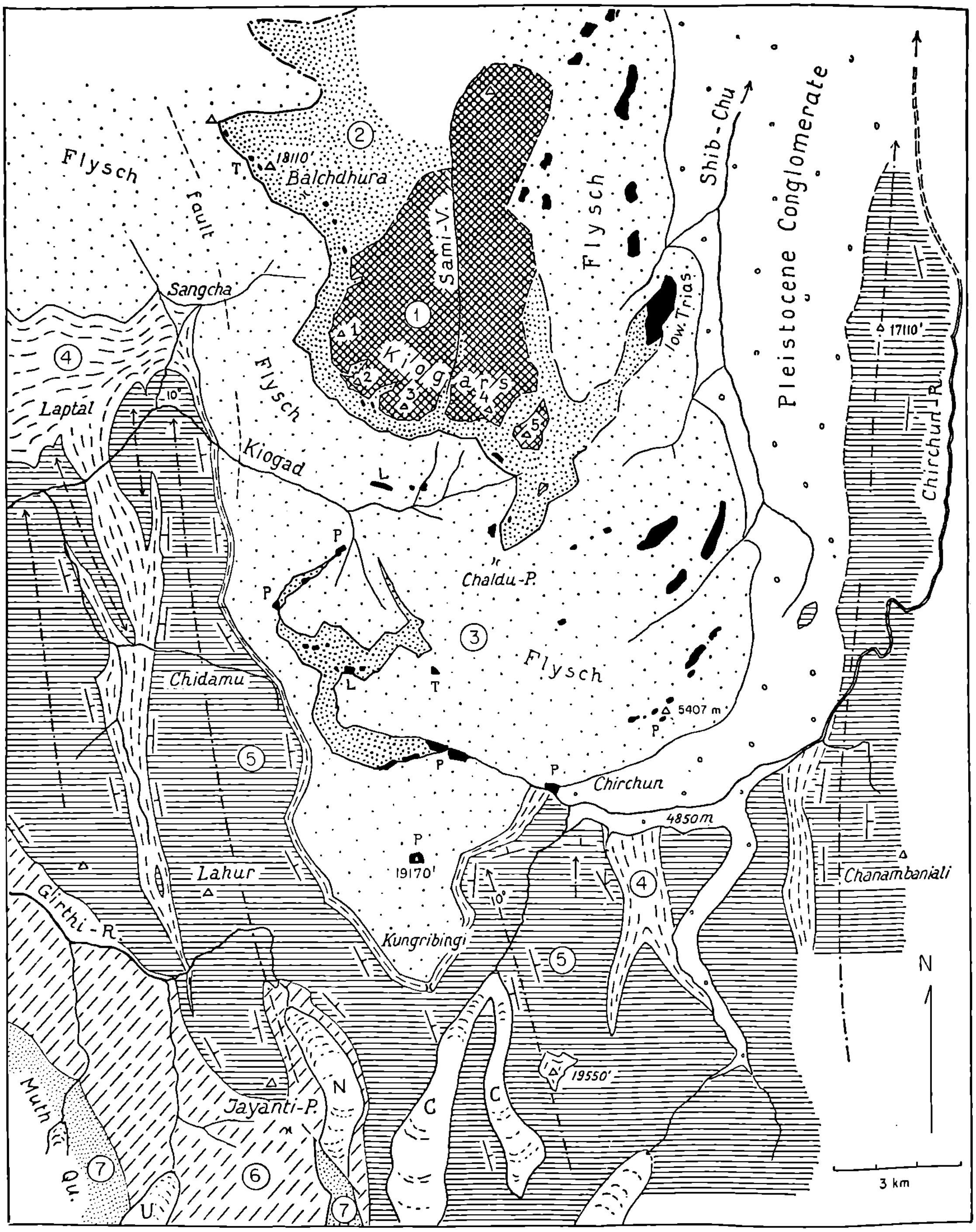


Fig. 80 *Sketch map of the Kiogar Chitichun region* (Tibetan Himalayas); after v. KRAFT (1902) and HEIM and GANSSER (1939)

1 Kiogar limestones, Trias-Jura, Tibetan facies
2 basic and ultrabasic rocks with exotic blocks
3 main Flysch with exotic blocks
4 Spiti shales Upper Jurassic
5 Kioto limestones (Rhaetian)
6 Kuti shales, Noric
7 Muth quartzites and older

black—exotic blocks, L—Liassic, T—Triassic, P—Permian

exotic masses with the Flysch are well exposed and their position is certainly true. This is the case with a large Lias block about 300 m long and up to 60 m thick south of the Kiogar Peaks. Sometimes blocks of various composition are clustered together mixed with volcanic breccias and tuffs, the whole embedded in the Flysch. On point 5407 m large fossiliferous Permian blocks are associated with red and white Triassic limestones (Fig. 82). Basic volcanics in direct contact with the limestones may be embedded in the Flysch as coherent units. It is not certain whether the blocks and volcanics are remnants of larger exotic block masses such as the exotic blocks mentioned below, now disintegrated and slipped, or whether they represent single and/or clusters of blocks occuring with the Flysch.

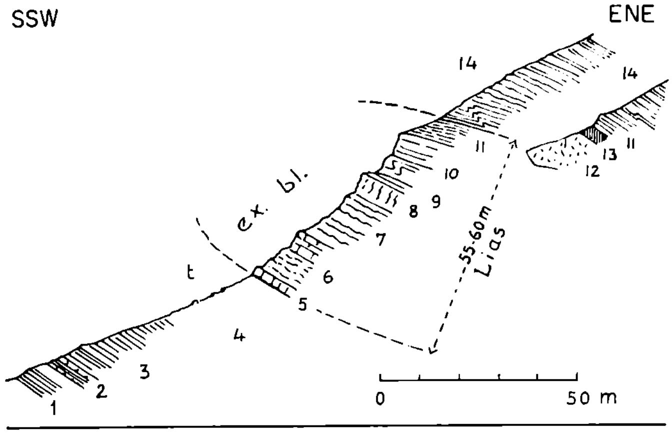


Fig. 81 *Section of Liassic exotic block within Cretaceous Flysch.* Kiogar region, Tibetan Himalayas; after A. Heim (1939)

1 variegated Flysch shales
2 red limestones
3–4 grey and black Flysch shales
5 dense red to pink cherty limestone
6 nod. limestone
7 red shaly limestones
8 red cherty limestones
(5–8: Lias in Adneth facies)
9 pink to violet marls
10 variegated limestones with radiolarians
11 red marly shales
(9–11: Lias in Adneth facies)
12 reddish limestone breccia
13 basic igneous
14 dark grey Flysch shales

Details of this outcrop are shown in Fig. 81. von Kraft was the first to discover *Arietites* and *Phylloceras* and he recalled the striking similarity with the Adneth facies of Austria. *Radiolaria* and sponge spicules are frequent in these pelagic and probably rather deep sea deposits, an otherwise unknown facies for the Himalayas. Several other similar Liassic blocks are known, all with fragments of basic volcanic rocks attached to them. To the southeast of the Kiogars a dark grey gloomy landscape opens out, with rounded Flysch ridges studded with pink to red limestone blocks.

2. *The exotic blocks in the basic vulcanites* form a consistent sheet, topped by the Kiogar limestone masses (Fig. 83). Within a most complex asso-

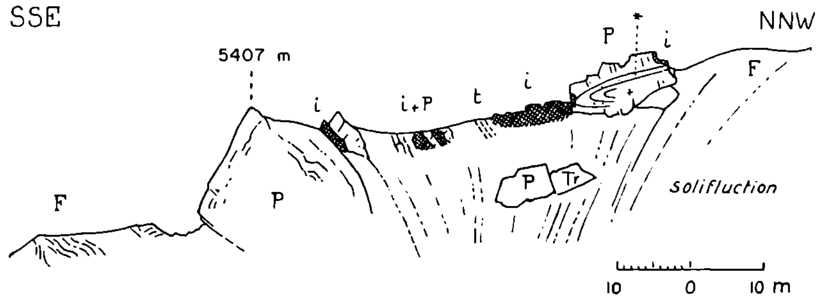


Fig. 82 *Composite exotic block at Pt. 5407 m* (see sketch map fig. 80) Kiogar region, Tibetan Himalayas; after A. Heim (1939)

F upper siliceous Flysch
P crinoidal *Productus* limestones with ammonites at *
i basic igneous
t green tuff
Tr red and white Triassic limestones

ciation of basic igneous rocks and related tuffs we observe a multitude of blocks of different composition. They are well exposed in the 5500 m high Balchadura area northwest of the Kiogars. The igneous masses consist of large serpentine sheets with zones of ophicalcite, some peridotites, diabases, basic, often amygdaloidal porphyrites and a great variety of basic tuffs mixed with some siliceous Flysch sediments. The embedded exotic blocks are mostly of Triassic or probably younger age. Permian and older blocks seem rare or missing. Frequent components are white Kiogar limestones (see below), red radiolarian cherts, dense brick-red limestones and marls. The volcanics, mostly basic porphyrites, are in direct contact with the limestones and rich in calcite alveoles near the contact zone. Of special interest is a small (15 cubic m) red limestone block fully embedded in porphyrites, which furnished a very rich Carnian cephalopod fauna quite distinct from the Himalayan facies. From similar blocks discovered by VON KRAFT, DIENER gives a list of 40 species of ammonites (DIENER, 1912). Quite surprising are a few blocks of glauconitic sandstone embedded in basic volcanics which are indistinguishable from certain Lower Cretaceous Giumal sandstones.

3. *The exotic mass forming the Kiogar Peaks* (1-5) is of particular interest since it represents a disrupted and highly broken sheet of dense to fine crystalline massive limestone, 200-300 m thick and covering an area of 20 square kilometres. It seems to be a thrust sheet rather than a large exotic block. Locally tightly folded and faulted, the Kiogars dip regionally to the north and disappear northwards below the thick Quaternary gravel deposits belonging to the Tibetan Sutlej Basin (Fig. 84). The limestones form imposing summits varying between 5600 and 5800 m in height (Fig. 83, Ph. 18 and 19).

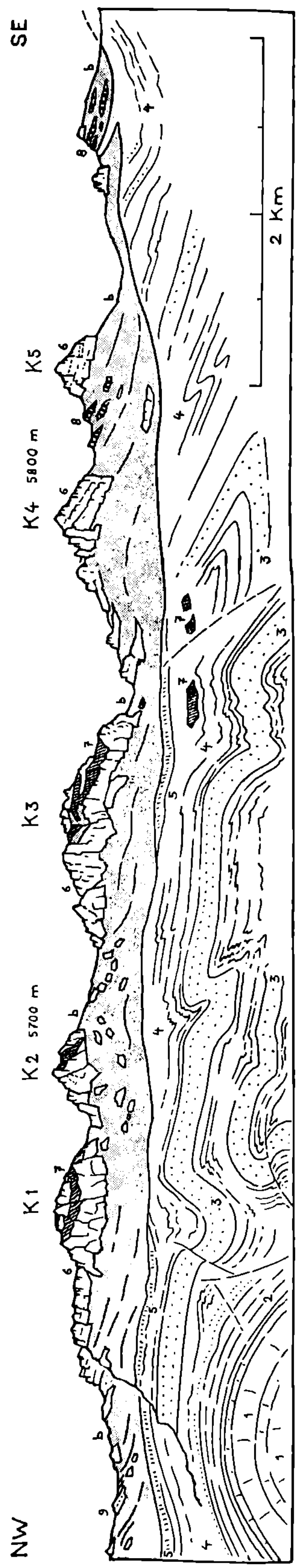


Fig. 83 *Section through the Kiogar Peaks,* Kiogar region Tibetan Himalayas; after HEIM and GANSSER (1939) and GANSSER (1959)

1	Kioto limestones (U. Triassic)	Himalayan Facies
2	Spiti shales	
3	Giumal sandstones (U. Cret.)	
4	silty red and green shales covered by dark grey fucoid shales (Flysch)	
5	siliceous sandstone with radiolarians (U. Cretac.)	
6	white Kiogar limestones (Trias?)	Tibetan Facies
7	oolitic limestones and calc schists with *Calpionella* (Up. Jur.)	
8	Radiolarites	
9	green sandstones	
b	basic and ultrabasic rocks with various exotic blocks from Permian to Cretaceous age	

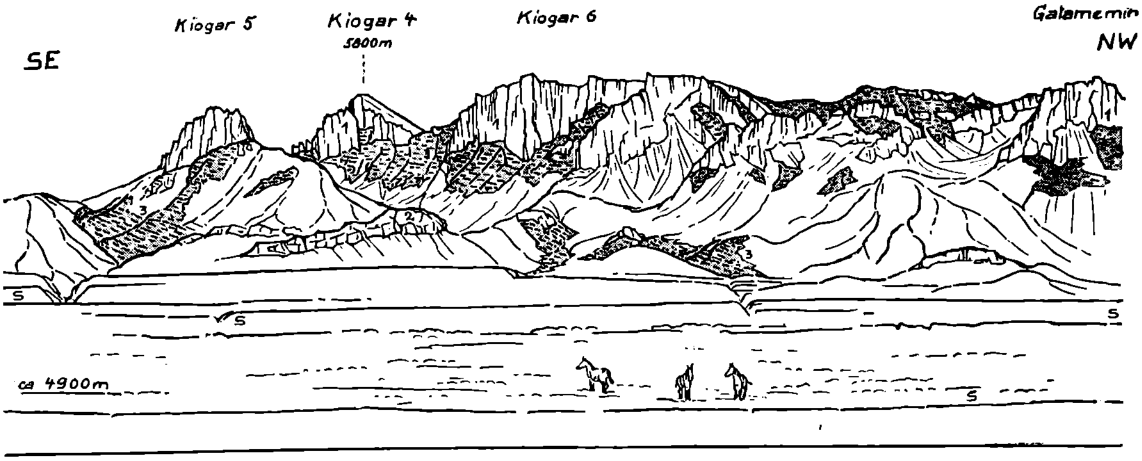


Fig. 84 *The Kiogar Peaks seen from the north.* Kiogar region, Tibetan Himalayas; after A. GANSSER (1939)

1 Kiogar limestones
2 red Lower Triassic limestones
3 Flysch with basic igneous rocks (not differentiated)
s Pleistocene terraces of the Sutlej system

In some peaks a certain stratigraphical sequence can be recognized. With a sharp, probably discontinous contact the Kiogar limestones are succeeded by red marls and limestones, violet oolitic limestones and grey well-bedded dense limestones rich in microfossils. The oolitic lime-

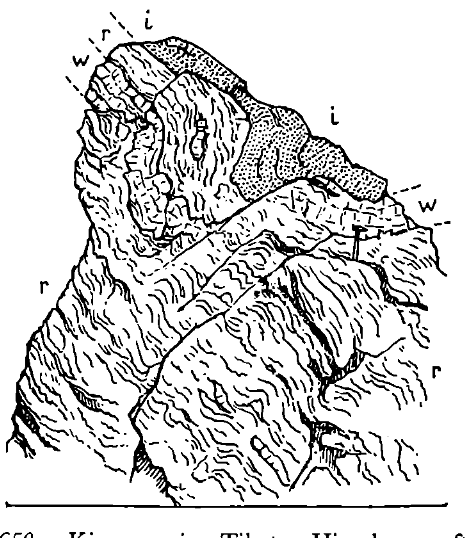


Fig. 85 *Detail at Kiogar Nr. 2 at 5650 m.* Kiogar region Tibetan Himalayas; after A. HEIM (1939)

r red and violet Upper Jurassic limestones
w white Jurassic limestones
i basic igneous rocks

stones are of particular interest since they have furnished Tithonian *Calpionellae* (Fig. 85). The grey limestones are rich in *Radiolaria* and sponge spicules, to which a Cretaceous age has been attributed. If this stratigraphical sequence is correct, the apparently unfossiliferous Kiogar limestones could be Upper Triassic, representing a facies reminiscent of the Alpine Dachstein limestone, as was long ago suggested by VON KRAFT. Such correlation would indicate two facies types for the Tibetan exotic Trias, as assumed by HEIM and GANSSER; this appears to be verified for the exotic blocks of the Amlang-La region, to be discussed in the next paragraph. The other suggestion, ventured by ARKELL (1956), that the Kiogar limestones could actually represent Lower Tithonian limestones in Alpine facies, would certainly simplify the stratigraphical sequence, resulting in only one exotic Tibetan facies. The two alternatives are indicated in the table below.

SYSTEM	TIBETAN FACIES after HEIM & GANSSER (1939)		TIBETAN FACIES after ARKELL (1956)
	Kiogar facies, main thrust sheet	Chirchun facies, fossiliferous exotic blocks of Chircun and Kiogar	
CRETACEOUS	Basic igneous. Shale and grey limestone with radiolarians	Basic igneous	? Grey radiolarian limestones
JURASSIC	Pink oolite and shale with *Calpionella alpina*		Kiogar oolite with *Calpionella alpina* Kiogar Limestone
			?
		Adneth Limestone with radiolarian chert	Adneth Limestone with Hettangian and Sinemurian ammonites
TRIASSIC	Kiogar Limestone	Red limestone rich in Carnian ammonites Red Middle Triassic limestone with *Ceratites*	Red limestone with Carnian ammonites Red limestone with *Ceratites*
PERMIAN		Crinoid limestone with Brachiopods	Crinoid limestone with Brachiopods

Phot. 20a and b *Calcareous algae (Dasycladacee) from exotic limestone blocks.* Upper horizon, Amlang-La (Tibet) a) Enl. 17× b) Enl. 6×

Phot. 21 *The exotic blocks south of Amlang-La* (Tibet). f = Flysch sandstone, mostly covered, c = Upper Cretaceous limestone, ex = exotic blocks of Lower Triassic, m = monzonites, cutting limestone discordantly (phot. A. Gansser)

Phot. 22a *Enstatite with drop-like segregations of augite in periodite.* Jungbwa, Tibet. Enl. 16×

Phot. 22b *Enstatite with segregation of lamellar monoclinic augite* parallel to the c axis. o = olivine from Jungbwa-peridotit, Jungbwa, Tibet. Enl. 35×

Phot. 23 *Olivine with stress lamellae* from the Jungbwa peridotite, Jungbwa, Tibet. e = enstatite. Enl. 17×

Phot. 24 *Chilmakurkur limestones with Megalodon-type shells.* Chilamkurkur Gorge, Tibet (phot. A. Gansser)

Phot. 25 *The Gurla Mandhata crystalline dome* (7700 m), (Tibet), seen from Tinkar Lipu, NW Nepal, with Triassic limestones in foreground. Note tilted terrace levels on northwestern plunge. To the left Kailas Range. View towards NE (phot. A. Heim)

Phot. 26 *Quaternary terrace levels on the west flank of Gurla Mandhata* in the upper Karnali Valley, Tibet (in foreground Jitkot Gompa). 1 = flood-plain of Karnali River, 2–6 = young to older terrace levels (phot. A. Gansser)

Phot. 27 *The gravel terraces ot the upper Sutlej,* along Sib-Chu, Tibet. ex = exotic blocks of Kiogar area, t = Quaternary gravel terraces, ch = Chilamkurkur range, p = Jungbwa peridotites, T = Transhimalaya range. View towards N (phot. A. Gansser)

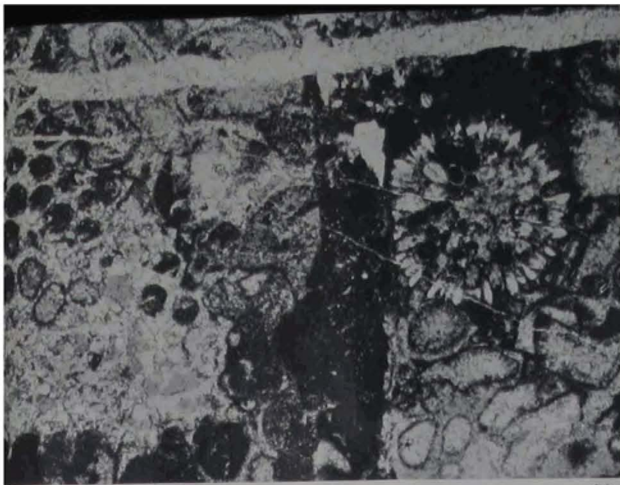
Phot. 28 *Thick Sutlej terraces in the Sib-Chu Gorge* with ancient cave dwellings (phot. A. Gansser)

Phot. 29 *The main thrust south of Kailas* (Tibet). Upturned Kailas conglomerates below the thrust line. F = Flysch, K = Kailas conglomerate (phot. A. Gansser)

Phot. 30 *Details of the main thrust south of Kailas* (Tibet). K = Kailas conglomerates with sandy shales and arkosic sandstones, sharply upturned below the thrust. F = red argillaceous sandstones and red and green conglomerates of the Flysch section, highly disturbed (phot. A. Gansser)

Phot. 31 *The massive to thick-bedded main Kailas conglomerate.* The Kailas granite follows just below the gravel in the foreground. West side of Kailas. Tibet (phot. A. Gansser)

Phot. 32 *Thin section of Kailas hornblende-biotite granite,* from north of Kailas, Tibet. mi = microcline, p = plagioclase, q = quartz, t = titanite, h = hornblende with relictic augite inclusions. Enl. 17×

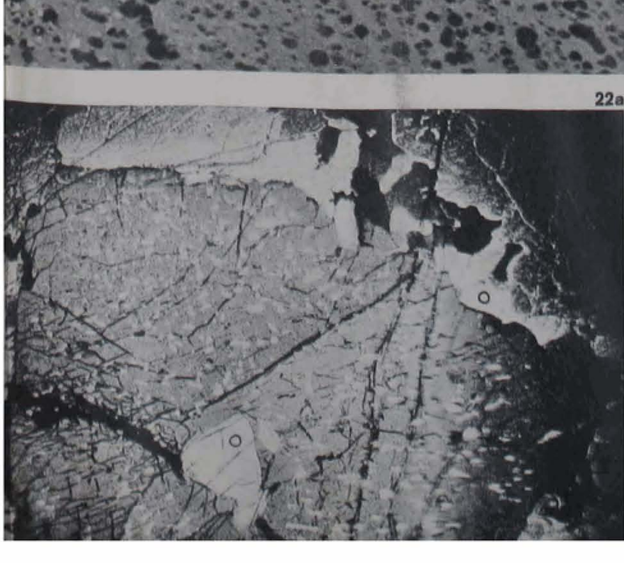


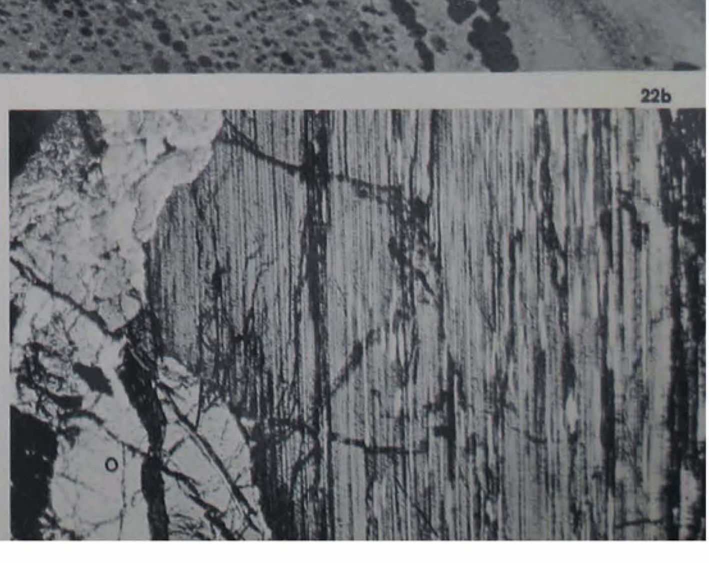
20a

20b

22a

22b





25 23

26

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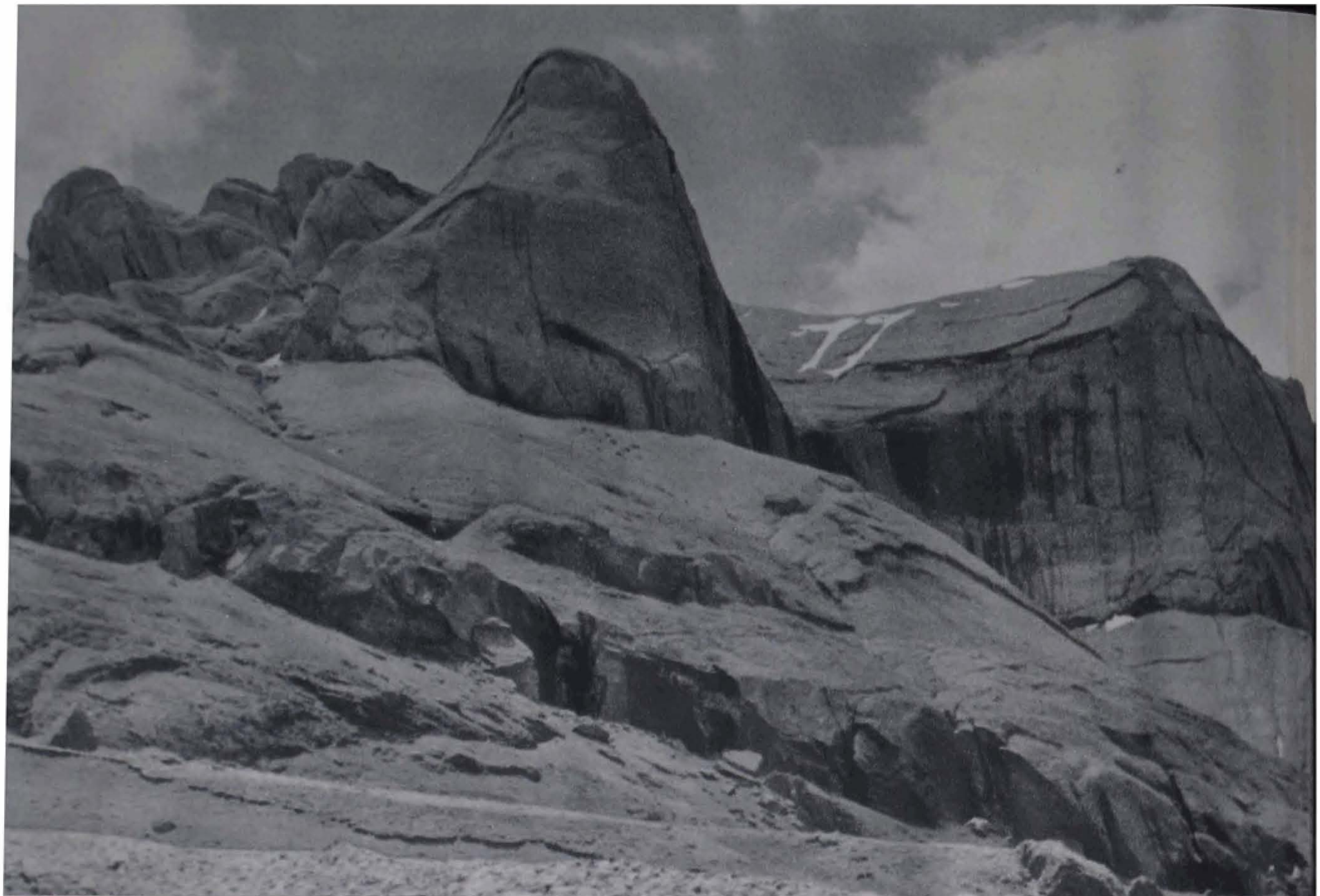

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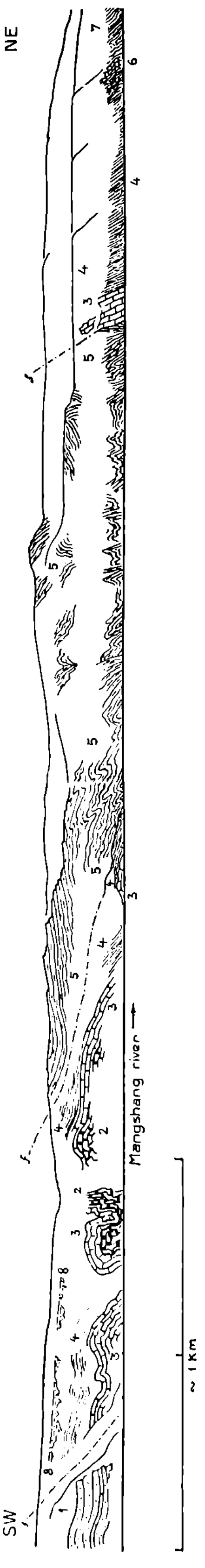


Exotic zone of Amlang-La

A more eastern south front of the Tibetan exotic masses was discovered by the author in 1936 while travelling to the Kailas Range, southwest of Raksas Lake, at the Amlang-La. This front does not conform to the general NW-SE strike of the Tethys Himalayas, but runs from the Kiogar region due east, a strike direction possibly influenced by the eastwards-rising dome-like old crystalline mass of the Gurla Mandhata. The change in strike is already evident in the Flysch deposits, forming the base of the exotic zone. They follow to the north of an extensive Jurassic series, distinct from the calcareous and slaty facies of the Tethys Himalayas. In the gently rolling gravel-covered landscape outcrops are rare, but along the *Mangshang River* an interesting section is exposed (Fig. 86). Disharmonic folding with some faults and thrusts complicate this section, but the large development of *arenaceous Jurassic* beds is of special interest. Following with an anomalous, possibly thrusted contact over strongly folded Palaeozoic and probably some Triassic rocks, one observes intricately folded fine micaceous slaty calcareous sandstones, with indeterminable plant remains. After a fault contact, black micaceous shales continue until a 100 m thick sandy limestone and shale section rich in large Middle Jurassic belemnites is met. More sandy intercalations contain plant remains similar to the sandstone section mentioned above. Black shales develop gradually upwards from the more sandy horizons. They contain some cherty concretions but during the rapid reconnaissance no fossils were seen. They may represent an equivalent of the Spiti section, but are at least 1000 m thick and have a very wide extension, reaching the Flysch at the base of the exotic zone, although the contact is not exposed. This arenaceous Jurassic, even with some plant remains, is unlike the normal Tethys Jurassic and resembles quite closely some of the Jurassic facies of Tibet as mentioned by HAYDEN. Unfortunately, the plants are badly preserved, otherwise a comparison with the Angara-type flora would have been most interesting.

Fig. 86 *The section along the Mangshang River.* Southern Tibet; after A. GANSSER (1939)

1 Quartzite, probably lower Muth section
2 brown limestone with corals (Devonian?)
3 white limestones with brachiopods and crinoid breccias
4 micaceous black shales
5 micaceous, slaty calcareous sandstones with plant remains
6 brown-grey sandy limestones with *Belemnopsis* (Dogger)
7 black slates, probably Spiti
8 Pleistocene gravel terraces

The Flysch section of Amlang-La is divided into a lower and upper section, each containing a horizon of exotic blocks. The intermediate zone is characterized by a conspicuous limestone, intruded by monzonites (Fig. 87, 88).

The lower Flysch begins with shaly sandstones and intercalated siliceous shales. The latter increase upwards, together with argillaceous chert horizons. Fine, well-bedded glauconitic sandstones occur in the middle part. They are arkosic, with angular quartz and feldspar grains and contain fragments of ophitic diabase, similar to the volcanics related to the exotic blocks. Some of the glauconitic sandstones are unexpectedly rich in *Radiolaria* and some foraminifera. After a few metres of calcareous sandstones follow sandy mostly dark brown to black shales which contain the *exotic blocks of the lower level.* They are topped by conspicuous calcite-veined well-bedded foraminiferal limestones, regarded as Upper Cretaceous, and which separate the lower Flysch section from the upper. The upper Flysch section follows with green siliceous shales, locally steeply folded and 200-400 m of light-coloured yellowish well-bedded sandstones and dark grey sandy shales which form the bulk of this upper part and contain the *higher exotic blocks.* In spite of local complications, the whole Flysch section, which is very well bedded, dips regionally at about 30-40° to the north, below the large synclinal mass of young peridotites, to be discussed below.

Both horizons of exotic blocks are clearly embedded within the Flysch. Compared to the Kiogar region, the size and amount of the blocks is somewhat reduced, and the blocks of the lower and the higher horizons are of a different composition. *The lower blocks* consist predominantly of white fine crystalline limestone veined and

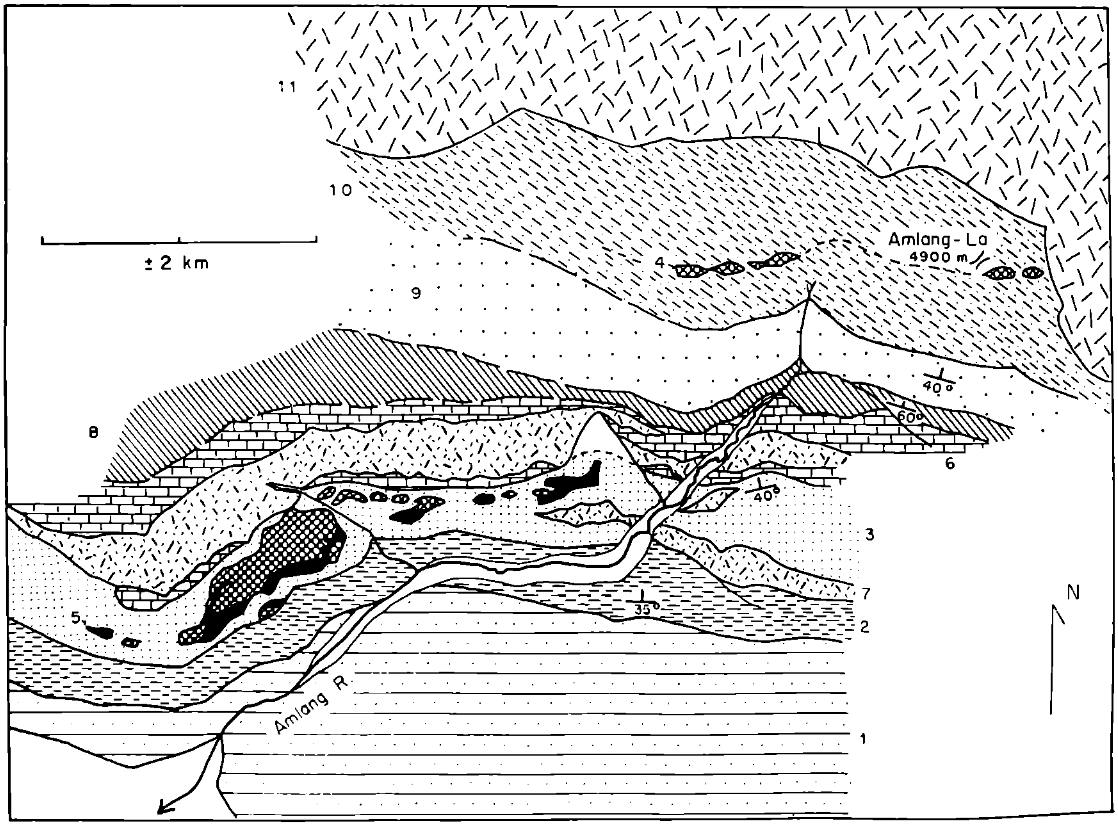


Fig. 87 *Geological sketch map of the Amlang-La region* (S Tibet); after A. GANSSER (1939)

1 sandy shaly Flysch
2 siliceous slates
3 glauconitic sandstones and silts with radiolaria (contain lower exotic blocks)
4 exotic blocks (lower level: red Triassic limestones with ammonites. Upper level: white limestones and fine-grained dolomites)
5 basic igneous and volcanics
6 Upper Cretaceous limestones
7 Post Upper Cretaceous monzonite
8 red and green siliceous silts and shales
9 yellow to white sandstones
10 sandy shales (contain upper exotic blocks)
11 the Jungbwa peridotites

irregularly intersected by a red limestone mass rich in Middle to Lower Triassic cephalopods. Brecciated parts in the white limestones are cemented with ammonite-bearing red lime. The similarity of these limestones to the "Alpine" Trias of the Kiogar region is striking. The largest block is 1000 m long and 200 m thick and is intruded by amygdaloidal green porphyrites. The latter can also form individual blocks within the Flysch. Most of the limestone blocks are and may be a precursory phase of the widespread peridotites (Ph. 21).

Covering the northwards-dipping Flysch and its exotic blocks follows a wide extension of fresh *peridotite*. This ultrabasic rock is surprisingly uniform, and only locally somewhat serpentinized. It extends over a surface of at least 3500 sq. km and in its central synclinal part may be over 500 m thick. The coarse-grained peridotite shows quite fresh olivines (forsterite) and some enstatite

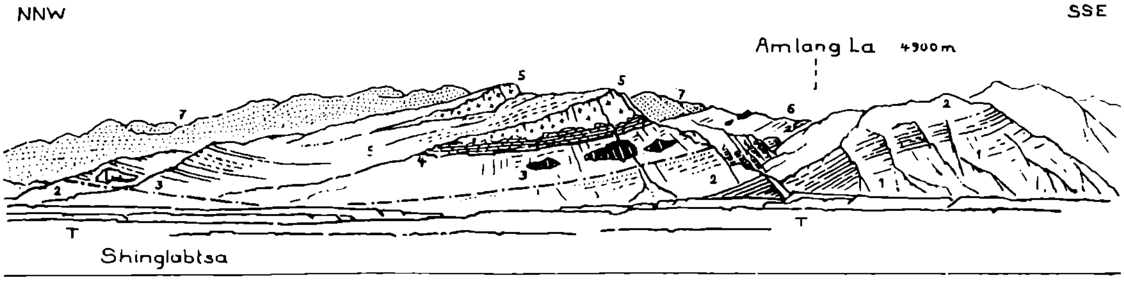


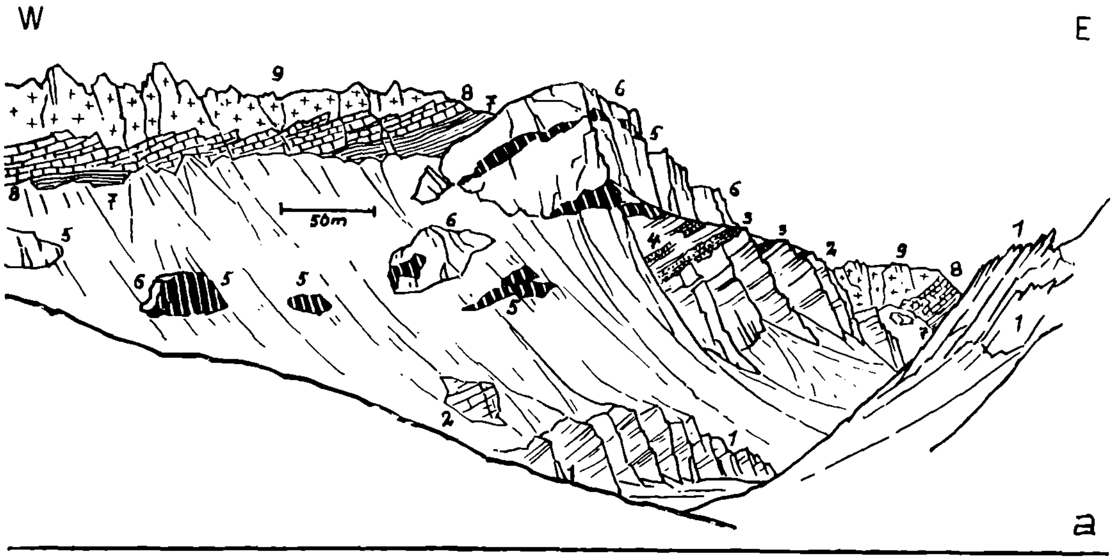
Fig. 88 *The zone of exotic blocks of Amlang-La.* S Tibet; after A. GANSSER (1939)

1 Lower Flysch
2 Upper Flysch
3 Lower zone of exotic blocks
4 Upper Cretaceous limestones
5 monzonite
6 Upper zone of exotic blocks
7 Jungbwa peridotites

embedded with some porphyrites attached. Within the Flysch there are also blocks of porphyritic tuffs and agglomerates. There is no doubt that the porphyrites are older than the Flysch, which contains some pyroclastic fragments, but younger than the exotic limestone blocks into which they were intrusive. In the *upper exotic horizons* only blocks of a white brittle and dense limestone were observed, with thin bands of dolomite. Some are related to basic volcanics. They are quite distinct from the blocks in the lower horizon and somewhat resemble the Kiogar limestones. Recently one of these blocks was reinvestigated. It consists of a dense creamy-white nodular limestone rich in calcareous algae (Ph. 20a and b). The algae seem to belong to the Dasycladaceae (cf. *Macroporella*) and one form resembles *Epimastopora* (PIA 1922). Since these forms range from the Palaeozoic to the Jurassic no age determination is possible.

The lower as well as the upper Flysch and particularly the dividing limestones, are intruded by *augite monzonites* consisting of alkali feldspars and andesine with borders of pigeonitic augite and biotite (Fig. 89a, b). The monzonites vary from fine- to coarse-grained—the finer with more dioritic, the coarser more syenitic affinities. At the contact the monzonite is fine-grained and the Flysch limestone shows a rim of fine marble a few centimetres broad. The age of the monzonite is clearly post-Flysch, possibly Eocene with interesting lamellar inclusions of monoclinic augite (Ph. 22a, b, 23). The coarse grains of the olivine and the augites as well as the lamellar segregation of monoclinic augite from a rhombic variety indicate that this enormous mass of ultrabasic rocks cooled rather slowly. No trace of the normal cover of this peridotite has yet been seen. It seems to overlie, basin-like, all other rocks, with the exception of the Quaternary terraces (Sect. 3, Pl. III).

Small remnants of peridotite were observed in the Kiogar region together with serpentines, and these basic rocks may be related to the large peridotite mass. The northern limit of the main peridotite mass lies near the west shore of the Raksas Lake at *Jungbwa*, a name suggested for the whole peridotite mass. Here the Flysch outcrops again, this time with a regional south dip and the same exotic block zones (see Section 3, Pl. III). The Flysch just below the peridotite is rich in red radiolarian chert, with well-preserved *Radiolaria*. Most of the exotic blocks are of the white and red Lower Triassic type containing ammonites, together with porphyrites. As a whole the Flysch and the exotic blocks at Jungbwa are somewhat reduced when compared with the Amlang-La region, but otherwise surprisingly constant in both areas. Neither in the south nor in the north, where the Flysch outcrops below the younger peridotites, have dykes of ultrabasic rocks been observed. The same holds true for the Kiogar region.



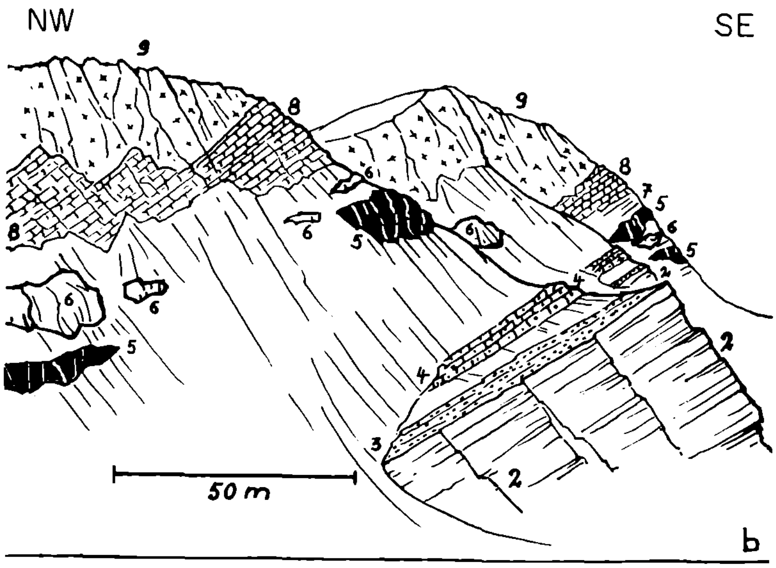


Fig. 89a, b *The exotic blocks south of Amlang-La.* S Tibet; after A. GANSSER (1939)

1 sandy siliceous Flysch
2 green siliceous shales and slates
3 reddish glauconitic sandstones with radiolarians
4 calcareous argillaceous sandstone band
5 porphyritic volcanics, as blocks in Flysch
6 Lower Triassic limestones
7 sandy shaly black to brown Flysch
8 Upper Cretaceous limestones
9 monzonite, intruding into 8

Exotic zone of Shib-Chu

Another extension of the exotic blocks was found by the author in the Shib-Chu Gorge north of the Kiogar region, during a traverse to the Sutlej River. The Shib-Chu, draining the Kiogar region, forms a gorge mostly cut through the thick Quaternary Sutlej terraces. Within this gorge excellent exposures of a strongly reduced exotic zone were found (Fig. 90). We have already noted that the Kiogars plunge northwards and are covered by the gravel terraces of the wide Sutlej Basin (Fig. 91). On their northwest side, the Jungbwa peridotites overly the Flysch, while older rocks, the Chilamkurkur formation, which will be discussed below, crop out to the east. Influenced by the Chilamkurkur uplift in the east, the Flysch of the Shib-Chu Gorge strikes abnormally northwards and dips at about 30-40° to the west. Calcareous sandstones

alternating with black silty shales compose the reduced Flysch section. On the top of the Flysch occur lenticular remnants of red and white limestone blocks, directly covered by the Jungbwa stones a conspicuous band of ophicalcite can be seen, with angular fragments of serpentine embedded in a matrix of large calcite crystals. This ophicalcite is not restricted to the limestone con-

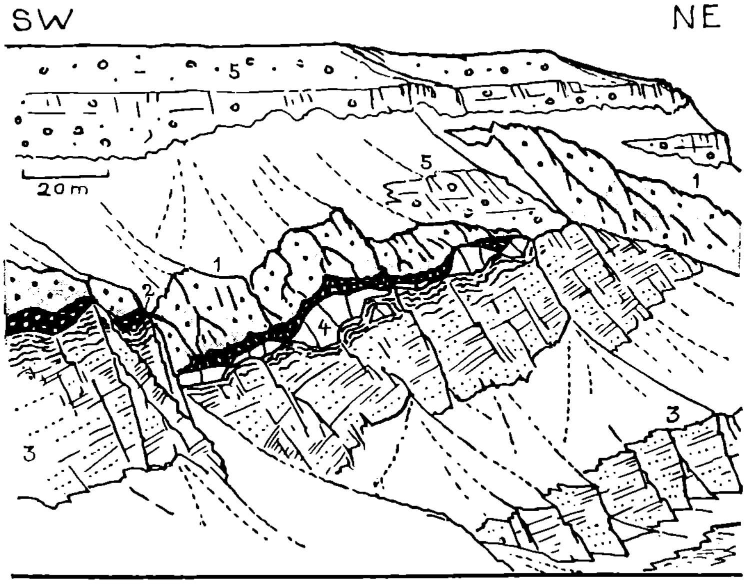


Fig. 90 *The reduced exotic zone in the Shib-Chu Gorge.* S Tibet; after A. GANSSER (1939)

1 Jungbwa peridodites
2 band of ophicalcites
3 sandy shaly Upper Cretaceous Flysch
4 white and red limestones (exotic Trias)
5 Pleistocene gravels of the Sutlej system

peridotites. They recall a *strongly boudinaged limestone horizon.* The Flysch shales are intensely crumpled under the exotic limestone lenses, which are comparable to the Triassic exotics (Fig. 90). Between the peridotites and the lime- tacts alone, but can be observed further to the north in the same gorge where the strongly reduced exotic blocks have now disappeared, and the Jungbwa peridotite transgresses unconformably onto the more strongly folded Flysch

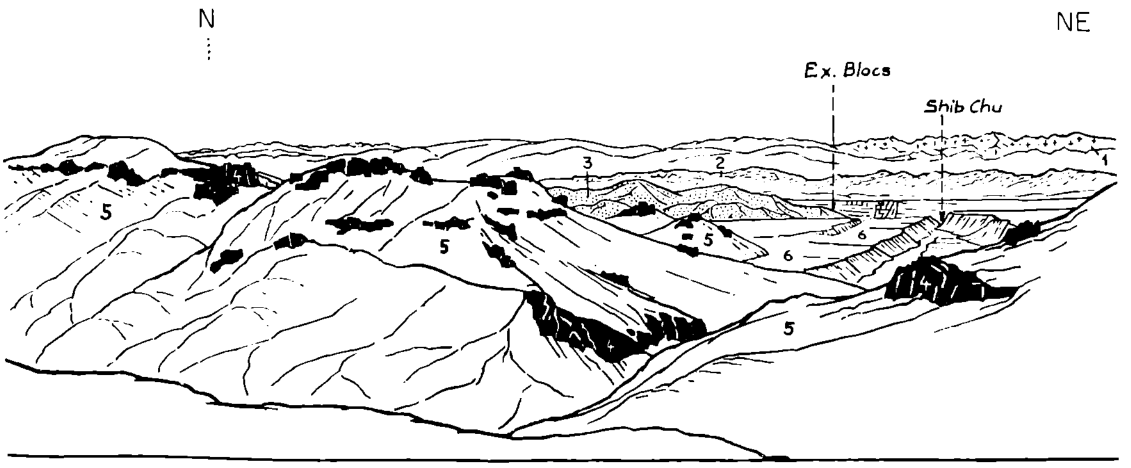


Fig. 91 *The north end of the Kiogar region,* view towards N. Tibetan Himalayas; after A. GANSSER (1939)

1 Kailas granites of Transhimalayas
2 Chilamkurkur zone
3 Jungbwa peridotites
4 the northern exotic blocks of the Kiogar region
5 Flysch with basic rocks, not differentiated
6 Pleistocene gravel terraces of the Shib-Chu, belonging to the Sutlej system

(Fig. 92). The clear exposures in the Shib-Chu Gorge as well as the section of Jungbwa indicate a *reduction of the exotic zone from the south to the north.* The exposures at Shib-Chu furthermore show that the reduction is to some extent tectonic (boudinaged aspect of the exotic limestones and the presence of ophicalcites).

Older formations outcrop all along the northern limit of the exotic rocks, and no further remnants have been observed. Only along the south front of the Kailas Range, in a northwards-thrusted Flysch zone, does a tectonized zone of exotic blocks reappear (see below).

discovery of deformed Liassic ammonites, one would suggest a much older age. This important stratigraphical marker places the upper black shales into the post-Lias and pre-Flysch and the following deeper zones into the pre-Liassic. Directly underlying are Flysch-like micaceous greenish-grey sandy shales recalling similar deposits south of Amlang-La. Then follows a more than 2000 m thick section of carbonates, mainly as bluish grey partly crinoidal and oolitic limestones which contain traces of larger gastropods and some lumachelles. Further west, towards the Sutlej Gorge in the Chilamkurkur Range

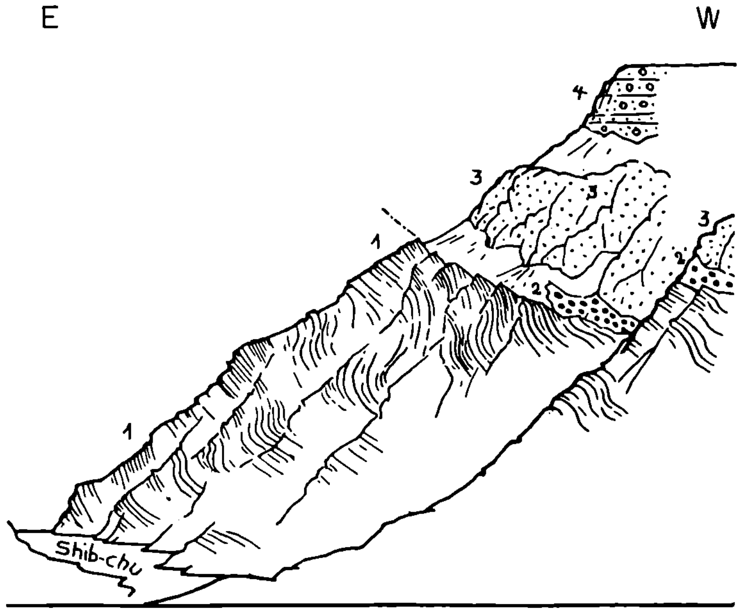


Fig. 92 *Transgression of the Jungbwa peridotites directly on the Cretaceous Flysch* without exotic blocks. Lower Shib-Chu Gorge. S Tibet; after A. Gansser (1939)

1 Upper Cretaceous Flysch
2 ophicalcites
3 Jungbwa peridotites
4 Pleistocene gravel terraces

Raksas anticlinorium

A wide anticlinorium of mostly Mesozoic and older sediments outcrops between the northern front of the exotic rocks and the wide alluvial depression following south of the foot of the Kailas Range, a part of the southernmost chain of the Transhimalayas.

In the region of Jungbwa, just below the northwards-rising Flysch thrust, are some outcrops of black shales, identical to the black shales which form the base of the southern exotic front south of Amlang-La and which have been regarded as an enlarged section of the Spiti shales. They form the south flank of the large Raksas anticlinorium. The next deeper horizons are greenish phyllitic clay slates, and if it were not for the similar limestones contain horizons crowded with thick-shelled megalodons (Ph. 24). It is possible that some of the limestones represent the Kioto limestones of Rhaetic to uppermost Triassic age and even Trias in a somewhat different facies (Fig. 93). No similarity with a fossiliferous Tethys Trias was noted and much less any indication of resemblance with the exotic Trias facies. In the Sutlej Gorge, 100 km to the WNW, the facies of the calcareous section is already different, with intercalations of conspicuous black slates (Fig. 94).

The core of the huge Raksas anticlinorium is formed by yellowish and greenish, more or less calcareous and chloritic, sericite schists, surprisingly recalling the Cambrian *Garbyang formation.* They form the lowest outcrops of the Raksas anticlinorium, which seems to plunge slightly in

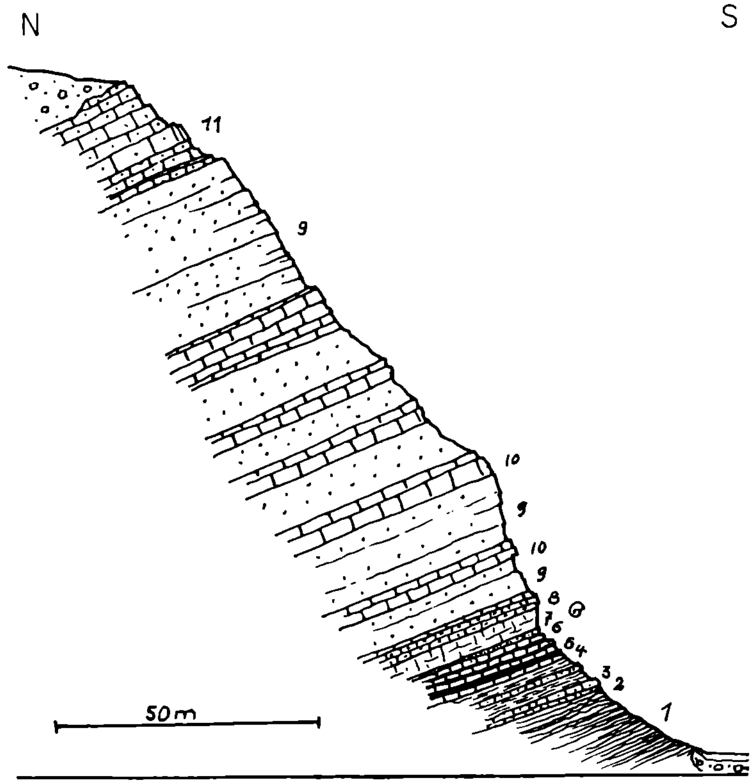


Fig. 93 *The Chilamkurkur series in the Sutlej Gorge* at Chilamkurkur. Raksas anticlinorium, S Tibet; after A. GANSSER (1939)

1 black slates
2 grey silty slates
3 brown sandstones
4 dark banded limestone
5 red slates alternating with 4
6 reddish sandy limestones
7 limestones with *Megalodon*-like shells (Ph. 24)
8 quartzitic sandstones
9 yellow-brown sandstones
10 dark grey limestones
11 thin-bedded and banded sandy limestones

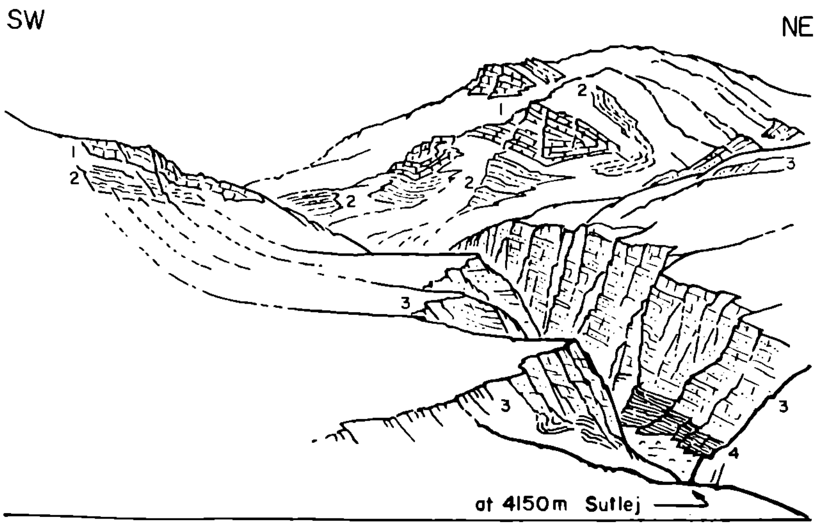


Fig. 94 *The Sutlej River cutting through the Raksas anticlinorium.* S Tibet; after A. GANSSER (1939)

1 Upper Chilamkurkur series (calcareous)
2 Lower Chilamkurkur series (argillaceous)
3 sandy calcareous schists
4 black slates

a western direction and extends eastwards towards the Manasarowar Lake. Its eastern continuation is unknown, except that it may rise and be connected to a northwards spur of the large crystalline dome of the 7700 m high Gurla Mandhata.

Crystalline dome of the Gurla Mandhata

Southeast of the famous lakes Raksas and Manasarowar the wide Tibetan rolling hills are dominated by a huge dome-like uplift—the 7700 m high Gurla Mandhata. The morphological aspects suggest a *very young uplift*. The well preserved domal form and the sharply eroded deep gorges as well as its excessive height support this suggestion (Fig. 95 and Ph. 25).

The outer layers are formed by epimetamorphic phyllites, while the inner core exposes muscovite-biotite gneisses, not unlike the Darjeeling-type gneiss (HEIM and GANSSER, 1939). SVEN HEDIN collected crystalline rocks from the northern slopes of Gurla Mandhata described by HENNIG (1915). He mentions banded to lenticular two-mica alkali-feldspar gneisses.

The western border of Gurla Mandhata is bordered by the young gravel terraces of Taklakot in the uppermost Karnali Valley (Ph. 26). They expose several well-outlined levels with increasing tilts towards the dome, well visible on its western plunge. They reflect the young uplift of this area. Mesozoic Tethys sediments strike eastwards under these terraces. On the north side, the belt of the exotic blocks of Amlang-La trends towards the north-plunging end of the Gurla Mandhata dome, but the direct relations are not known, since here again uptilted terraces mask the contact. The Gurla dome seems a southern, and higher, equivalent of the Raksas uplift. Whether the two are directly connected across a saddle in the north is not known. Both seem to be authochtonous and could, as we have already mentioned, be compared to the Tso Morari uplift in the Rupshu area, described by BERTHELSEN (1953).

Sutlej Gravel Terraces

The conspicuous gravel terraces of Taklakot represent the easternmost extension of the well-developed gravels of the upper Sutlej Basin, covering an area of about 6000 sq. km into which the Sutlej River and its tributaries have cut impressive canyons with depths of up to

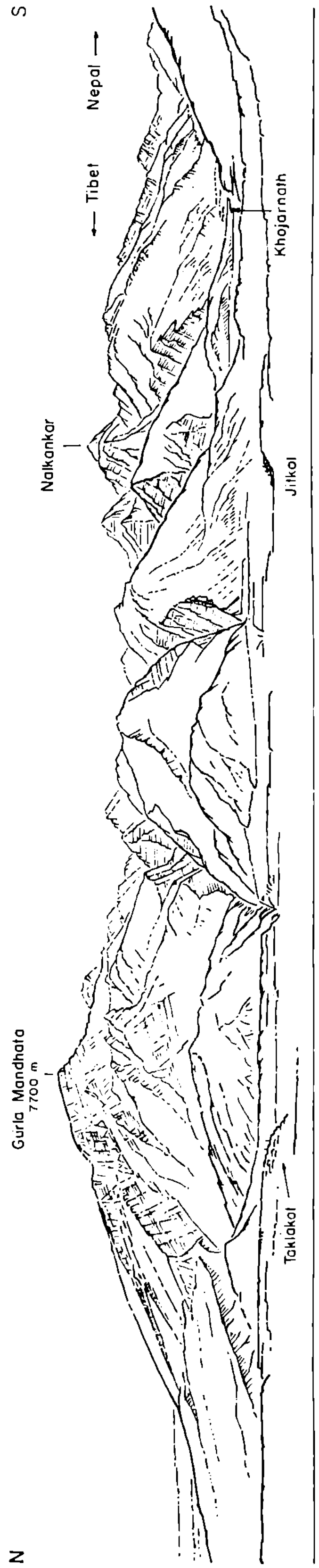


Fig. 95 *The gneiss dome of Gurla Mandhata.* S Tibet; after A. GANSSER

core of gneisses, covered by schists transgressed by tilted terraces of the Taklakot region, uppermost Karnali Valley

1000 m. From this region, generally called Hundes, GRIESBACH (1891) reports some nummulitic sandstones from the southern margin of the basin, northeast of the Niti Pass. He compares these nummulite-bearing deposits with the Lower Tertiary of the Indus Basin. It is not known how much of the wide extension of Pleistocene terraces is actually underlain by Lower Tertiary. Most of the younger gravels transgress directly over older, mostly pre-Tertiary rocks (Fig. 96, Ph. 27).

The gravel horizons are mostly coarse-grained, the pebbles and boulders well rounded. They are well bedded with sandy and silty intercalations. They form impressive cliffs in the Shib-Chu Gorge, where they cover the last remnants of the exotic blocks discussed above (Fig. 90, 91). The vertical walls have been a preferred site for old cave dwellings. A whole monastery was discovered by the writer in the lower Shib-Chu Gorge (Ph. 28). The first investigators of Hundes (GENERAL STRACHEY, 1851; LYDEKKER, 1881) reported fossil mammal bones from the gravel deposits. LYDEKKER stressed the fact that the extinct genera, living during the deposition of the Siwaliks, are missing and that the Hundes fauna, more related to living species, represents most likely a Pleistocene to sub-Recent age.

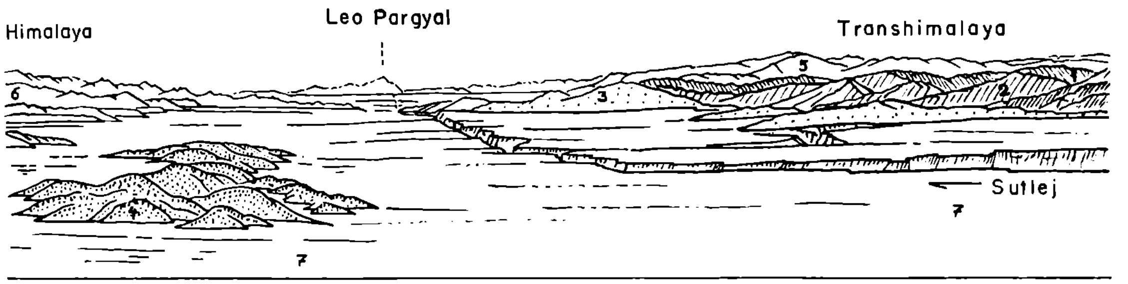


Fig. 96 *General view of the Upper Sutlej Basin,* view towards NW. S Tibet; after A. GANSSER (1939)

1 Lower Chilamkurkur series
2 Upper Chilamkurkur series
3 Flysch zone
4 Jungbwa peridotites
5 zone SW of Gartok, probably crystalline
6 sediments of Tethys Himalayas
7 Pleistocene to Recent Sutlej gravels

Kailas Range (Southern Transhimalayas)

While travelling from the Tethys Himalayas of Kumaon northwards further into Tibet, we have so far not met the northern border of the Himalayas, but have become involved in the more intriguing problems of the huge exotic thrust masses. Only on reaching the Kailas Range in the Transhimalayas is it possible to find some conclusive evidence for this northern limit.

Kailas Flysch

After the last gently north-dipping outcrops of the deeper Raksas phyllites one crosses a sandy alluvial plain of over 20 km before reaching the foothills of the Kailas Range. This plain hides one of the geologically most important stretches of the whole Himalayas. South of the Kailas the foothills consist of a highly complex and steeply south-dipping *Flysch zone* (the Kailas Flysch) with intercalated ophiolites and some exotic blocks. To the west, this Flysch zone is cut out, and the northwards-outcropping Kailas conglomerates reach the alluvial plain. Eastwards the Flysch continues, but its extension is unknown. The Kailas Flysch represents the last remnant of the Himalayas, thrust steeply northwards over the authochtonous Kailas conglomerates which transgress over the Kailas granite (Sect. 3, Pl. III).

It is evident that we have here one of *the key sections of the Himalayas*—its well-exposed northern limit. But it also happens to be a very holy place—the Kailas Mountain is sacred to Asiatic religions. Geological investigations, at least during 1936, could only be carried out "on the sly". What I describe here are the results of a rapid reconnaissance work, which gives the general outline but leaves much remaining to be done for a more detailed picture.

The first (southernmost) outcrops of the Flysch zone consist of a most complicated schuppen zone of sericitic sandy slates, red sandstones, slates and red radiolarian chert. They are intruded by massive enstatite-bearing serpentine which is associated with lenses of yellowish to white dolomitic limestones. These limestones are strikingly similar to certain exotic blocks, and the serpentine, which still shows the characteristic mesh texture of altered olivine, together with

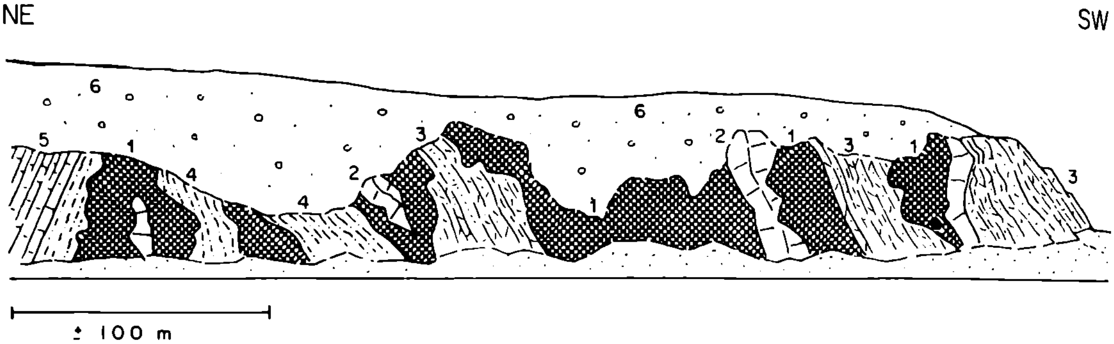


Fig. 97 *The southern Kailas Flysch zone.* Darchen, Kailas region. S Tibet; after A. GANSSER (1939)

1 serpentinized peridotites
2 white dolomitic limestones (exotics)
3 red sandy slates and cherts
4 sandy sericitic shales
5 well bedded limestones
6 gravel terraces

enstatite, is identical to the Jungbwa peridotites, which are younger than the Flysch (Fig. 97). The whole section dips steeply to the south. Going north we first meet with a zone of vertical limestones, and then with another south-dipping series, several thousand metres thick, of intensely folded grey phyllites, calcareous sandy schists and slates. On their southern border they contain a layer of red calcareous conglomerates which seems to be repeated towards the north together with some pyroclastic reddish calcareous sandstones. This whole mass of slightly metamorphic Flysch is thrust along a well-exposed and 30-40° south-dipping sharp tectonic contact over the thick and horizontally bedded Kailas conglomerate (Ph. 29, 30).

There is hardly any doubt that this Flysch section with its ultrabasic rocks and included exotic limestones corresponds to the exotic thrust mass of the Kiogars, Amang-La and Jungbwa. The thrust is clearly north directed, as we can recognize at the upturned Kailas conglomerates (Ph. 29, 30). *This thrust divides the Himalayas from the Transhimalayas*, the allochthonous from the autochthonous, along a sharp contact (Sect. 3, Pl. III).

The general strike of the Flysch mass is practically E-W whereas the Kailas Range and thrust line direction strike WNW-ESE. This means that the various units of the Flysch zone run obliquely against the thrust line. We noticed a quite similar descrepancy at the south front of the exotic thrust mass, which also strikes E-W and obliquely to the strike of the Tethys Himalayas. This coincidence is interesting, but could be merely accidental, since the two fronts are over 100 km apart, and only a very short section of the northern front has as yet been investigated.

Kailas Conglomerates

North of the thrust we enter a completely different region, characterized by huge fantastically shaped conglomerate mountains sitting on granites, of

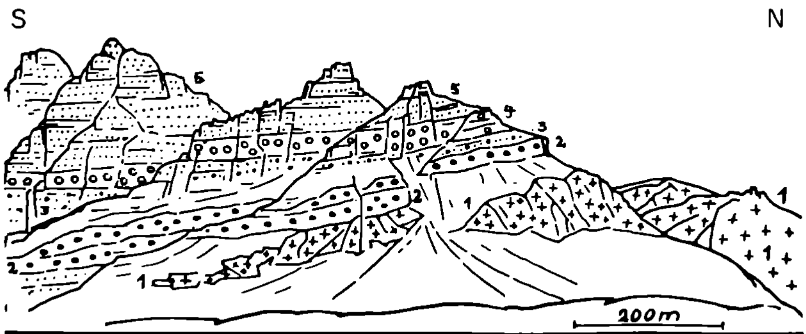


Fig. 98 *Transgression of the Kailas conglomerates on Kailas granite.* NW Kailas, S Tibet; after A. GANSSER (1939)

1 Kailas hornblende-biotite granite
2 basal conglomerate with granite boulders up to 5 m³
3 fine conglomerate rich in granite pebbles
4 coarse conglomerate with predominantly volcanic pebbles and boulders
5 main conglomerate with volcanic pebbles

which the 6700 m high Kailas itself is a surprisingly imposing and beautiful example (Ph. 31, 33). The horizontally bedded conglomerates reach from 4700 m to the top of the Kailas, i.e. there are some 2000 m visible. Their actual base north of the thrust must be at least 1000 m deeper, and since the Kailas is only an erosional remnant, the top of the conglomerates must have been even higher. We thus arrive at an astounding thickness of over 4000 m of undisturbed near-horizontal coarse detrital deposits. Sandstones are rare and increase slightly in a southern direction.

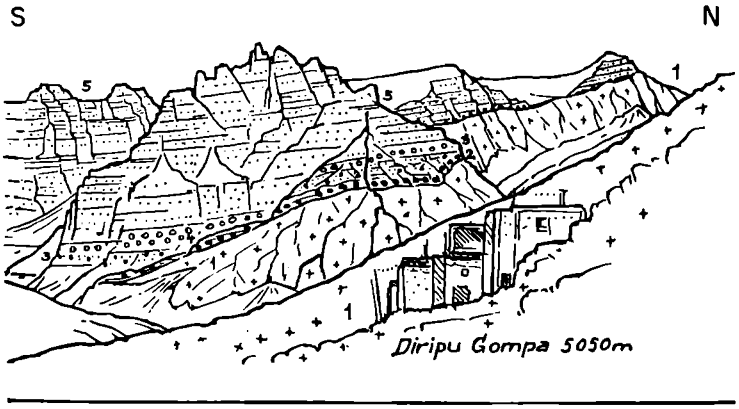


Fig. 99 *The south plunging Kailas granite with the transgression of Kailas conglomerates,* N of Kailas, S Tibet; after A. Gansser (1939)

for legend see fig. 98

The conglomerates are thick-bedded and near the Kailas some massive horizons can be 500 m thick (Fig. 98, 99). They transgress over an uneven surface of the Kailas granite with a basal boulder bed consisting of rounded granite boulders up to 5 cubic metres. They are embedded in a matrix of smaller granite pebbles and coarse arkosic sand grains. Upwards their size decreases and gradually well-rounded pebbles and boulders of colourful acid volcanics appear. Again a coarse conglomerate layer follows, consisting of 100 m of large boulders (up to 1 cubic m) of acid volcanics, quartzites and some red cherts. Higher up, the pebbles are smaller, usually less than head size, with a predominance of well rounded *volcanic rocks.* These volcanics represent liparites, dacites, andesites, granophyres as well as liparitic and dacitic tuffs. Granitic pebbles are very rare, metamorphic components and carbonate rocks seem to be missing completely, except for one 2 cm pebble of a yellow limestone. The pebbles diminish in size from north to south as well as from the bottom to the top. The matrix is usually coarse-grained, sandy and siliceous, but not calcareous, a fact which distinguishes the Kailas conglomerate amongst others from the Flysch conglomerates. From the matrix subordinate sandstones can develop, mostly greenish grey and arkosic in composition.

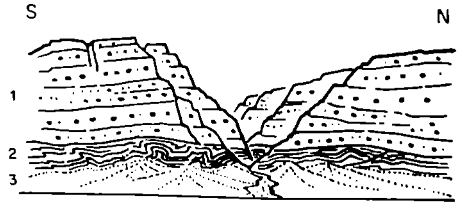


Fig. 100 *Disharmonic folds in sandstone intercalation at the base of the main Kailas conglomerates.* Folds increase approaching the main thrust, E. Kailas, S Tibet; after A. Gansser (1939)

1 main Kailas conglomerate
2 shaly sandstones
3 scree

In the north, where the conglomerates overlap the Kailas granite, the regional dip is about 10° to the south. Southwards this dip diminishes to about 2-3° (Fig. 99). The almost horizontal layers can be followed southwards until the thrust of the Himalayan Flysch is reached. Here one is struck by the sudden upturning of the horizontal conglomerate beds into an overturned position. This fact is very well visible in the field (Ph. 29, 30). Approaching the thrust, some of the smaller intercalated sandstones gradually show intense disharmonic folding, while the conglomerates are still undisturbed (Fig. 100). Only very near the thrust is some secondary folding visible within the conglomerate layers.

The distribution and size of the conglomerates and sandstones clearly indicate that the conglomerates have been *deposited from north to the south,* and originated north of the Kailas granite. The acid volcanic components are a rock type unknown in the south, but are similar to some

volcanic rocks collected by SVEN HEDIN north of the Transhimalayas and described by HENNIG (1916). Nothing is known of the lateral extension of the Kailas conglomerates except that they seem to continue eastwards along the Transhimalayan foothills, while their westwards extension seems limited.

The age of the conglomerates is still questionable. They are certainly younger than the Kailas granite, and the latter, as we will see, could be correlated with the Cretaceous Kyi-Chu granite of Lhasa (HAYDEN, 1907). They are older than the thrust of the Himalayan Flysch and most likely should be placed between the Eocene and the Miocene.

Kailas Granite

The Kailas conglomerate transgresses with a normal stratigraphical contact over the *Kailas granite,* which rises northwards from underneath the conglomerate and forms a wild granite landscape north of the Kailas Mountain. The granite, with its sharp peaks, has a strong irregular cleavage, and produces a coarse scree. It is generally rather fresh up to the transgression of the conglomerates. In the Kailas region the granite is completely massive, but further to the north it seems to become somewhat gneissified. The main rock type is a hornblende-biotite granite, medium-grained with alkali feldspars not exceeding 2 cm. These are mostly microcline while the plagioclase is oligoclase to andesine. Most interesting are the hornblendes, with sieve-like relics of augite (Ph. 32). The latter have a uniform extinction and seem to have been the primary constituent. Sphene is frequently associated with the hornblende. These facts are important for the correlation of the granites. They frequently contain more basic inclusions of a hornblende-dioritic composition. Here again the hornblende is characterized by augite inclusions. A few tourmaline aplites cut through the granite, but other dykes are absent or rare.

Practically nothing is known so far about the *extension of the Kailas granite.* From the few samples collected by SVEN HEDIN north of the Kailas region, the Kailas granite seems to change into liparite and dacites. The latter are very widespread and intrude Middle Cretaceous *Orbitolina* limestones (HENNIG, 1916). Westwards, along the foothills of the Transhimalayas, granite has been recorded again by SVEN HEDIN at Gartok—determined by HENNIG as a biotite-hornblende granite which seems quite similar to the Kailas granite. There too, dacitic lavas seem to occur further to the north. Another granite occurence similar to the Kailas granite has been reported by HAYDEN. It outcrops along the Kyi-Chu Valley, from the Tsangpo to beyond Lhasa. This granite is also a hornblende-biotite granite, but differs from the Kailas granite in the amount of albite and a certain carbonate content. It seems to be intrusive into Jurassic (and Cretaceous) calc-schists and is thus of late Cretaceous or younger age (HAYDEN, 1907). HAYDEN stresses the difference between the hornblende-bearing Kyi-Chu granite and the mostly hornblende-free normal Himalayan granites (see later).

From the Ladakh Range at Leh, WYSS (in VISSER, 1940) describes several biotite-hornblende granites not unlike the Kailas granites and suggests a pre-Senonian age. A possible connection with the Ladakh granites via the Gartok granites is possible, but too many gaps still exist to permit more than purely speculative correlation.

The regional problems of the northern Kumaon Himalayas up to the Kailas Range will be discussed later. So far only the main facts of this remote and still little-accessible region have been given. Emphasis had to be placed on this northern area, since further to the east along the northern Himalayas, our information remains exceedingly scanty or is missing altogether.

CHAPTER VII

NEPAL HIMALAYAS

The Nepal Himalayas, with an extension of 800 km, cover the mountain ranges lying within the Kingdom of Nepal.

Since 1949, when Nepal opened its border to foreigners, an intense geological investigation has taken place, and in a short time Nepal has become one of the geologically well known tracts of the Himalayan range. Prior to this date Nepal had received only very few sporadic visits. The earliest reported visitor was HOOKER, who in 1848 crossed the Tamur Valley in eastern Nepal (HOOKER, 1854). He was followed by MEDLICOTT, who investigated the Katmandu region and the Trisuli Ganga (MEDLICOTT, 1875). The first comprehensive account of Nepalese geology has been given by AUDEN (1935). It is based on his traverses in central and eastern Nepal in connection with the large Bihar earthquake in 1934. HEIM and GANSSER (1939) entered northwestern Nepal in 1936 where they discovered the Norian faunas already mentioned under Kumaon Himalayas.

In 1950 T. HAGEN began his field work for the Government of Nepal. During 10 years of intensive investigations in practically all parts of the now accessible kingdom he accumulated a wealth of geological facts, unequaled in the history of geological exploration in the Himalayas. In several preliminary publications some of his results are outlined, centering mostly on the tectonic aspect. He was able to assess the regional structure of Nepal and introduced a multitude of large and secondary nappes. Some of his structural subdivisions are difficult to follow, since a convincing stratigraphical control, particularly in the southern belts, is so far missing. This difficulty, evidently related to the virtual absence (with two exceptions) of fossils in the Lower Nepal Himalayas is further increased by the selective metamorphism. It seems almost impossible in various areas to decide whether a metamorphic zone corresponds to the base of a thrust or to internal features within a thrust zone. HAGEN's newest and first comprehensive compilation on the geology of Nepal, now in preparation, suffers from the same shortcomings. In spite of this, HAGEN's forthcoming publications and particularly his general geological map of Nepal are eagerly awaited, since they will form an important basis for all subsequent investigations in this part of the Himalayas.

During the last dozen years Nepal, together with the accessible Karakorum, has been the battle ground of the high mountain expeditions in the Himalayas, as all other regions with their rigorously kept "inner line" have been practically closed to foreign investigations. The spectacular array of 9 then-inviolate summits of over 8000 m (including Shisha Pangma) was incentive enough. Since it has become fashionable to attach a scientific label to alpinistic undertakings, many of the great expeditions did some geological investigation. If the geologist can remain independent, he will be able to accumulate valuable facts, but if he becomes involved in the logistics of a climbing expedition, the scientific aspect is hampered to a large extent. Such independent work was done by LOMBARD during the first Swiss Everest expedition and again by BORDET during the French ascents of Makalu. The excellent geological results of these expeditions are a valuable contribution to this highest mountain group.

Only in the northern region of Central Nepal do the Tethys Himalayas overlap into Nepalese territory. The easily accessible northernmost spur of Nepal, the region of Thakkhola, has therefore been covered by five geological investigations. HAGEN was the first; he was followed by BORDET (1957). In 1962 the Dutch geologists EGELER and DE BOY were in the same area; in early 1963 G. FUCHS of the Austrian expedition and in late 1963 BORDET with REYMAND and KRUMMENACHER covered the Thakkhola region again. It will be interesting to note and to compare the different views arrived at by different investigators in the same region. Already the comparison of the three general sections from Everest to the Ganges Plain by three different authors (Fig. 103a, b, c) demonstrates the freedom in the interpretation of a difficult mountain area which has been newly investigated.

Following the procedure applied in the previous chapters, the Nepal Himalayas will be subdivided into Sub-Himalayas, Lower Himalayas, Higher Himalayas and the Tibetan or Tethys Himalayas.

SUB-HIMALAYAS OF NEPAL

The Nepal Sub-Himalayas are exclusively built up of Siwalik and younger deposits, bordered by the Main Boundary Fault of the Pre-Siwalik Lower Himalayas. The Siwalik belt of Nepal is structurally better differentiated than in the Kumaon section and in general the Siwalik foothills occupy a wider belt. This fact is responsible for the recent detailed investigations carried out in view of the oil possibilities of the Nepalese foothills, but very little has so far been published. In southwestern Nepal, the maximum width reaches 52 km, while a few kilometres just east of the Arun River in eastern Nepal the alluvial plain extends right up to the Lower Himalayas.

HAGEN (1959) has published a most valuable set of maps (1: 500,000) with 95 cross sections covering the Siwalik belt of Nepal. He discusses the structural aspect of this belt but does not enter into lithological and stratigraphical details and refers in this respect to the previously published Siwalik literature. He does show, however, that the general three-fold division into Lower, Middle and Upper Siwaliks is also applicable to the Nepalese Sub-Himalayan belt and stresses the constancy of the deposits, assuming on one hand a longitudinal distribution on the lines of PILGRIM's Indobrahm, and on the other hand the local and direct influence of the Upper Siwaliks on ancient rivers related to the present north-south-directed valleys. He believes that most of the visible Siwalik sediments belong to the Middle Siwaliks. Lower Siwaliks occur only in narrow zones in south Central Nepal and in the western foothills. Upper Siwaliks are missing in the eastern foothills and are only well developed in the central and western Sub-Himalayas.

AUDEN (1935) describes Siwalik sections of central and eastern Nepal in some detail. West of the Sapt Khosi (river) AUDEN distinguishes as *Lower Siwaliks* an alternation of brown weathered sandstones and chocolate clays not unlike the Nahans from the type locality. In addition some beds of impure limestone occur. The *Middle Siwaliks* form great cliffs of sandstones, conspicuous by their feldspar and mica content, and apparently derived from granitic rocks. Their lower part contains some calcareous concretions as well as small lenses of coal. The locally preserved *Upper Siwaliks* are conglomeratic with the following pebbles and boulders: predominantly pale schistose quartzites, purple and white quartzites, dark phyllites, arkoses, purple and dark pebbly quartzites, silty brown sandstones, and tourmaline aplites.

Except for the brown sandstones, all pebbles represent rocks of pre-Tertiary age. The tourmaline aplite may belong to the youngest dyke system. The lack of metamorphic rocks, forming at present most of the adjoining hinterland, is striking.

LOMBARD (1958) describes from west of the Sapt Kosi regularly north-dipping massive and homogenous sandstones, with increasing cross bedding towards their upper part, together with calcareous concretions. Mottled reddish clays and marls are intercalated. The upper horizons contain bluish clays with conglomeratic layers. No stratigraphical subdivision is given. BORDET (1961) mentions Siwalik outcrops east of the Arun Gorge (SE Dharan Bazar). He stresses the cyclic deposition beginning with coarse, locally conglomeratic sandstones with phyllitic pebbles grading upwards into cross-bedded micaceous sandstones (with detrital biotite) containing some intraformational pelitic pellets and lignitic seams. The top is formed by greenish to blackish clays, followed again by coarse sandstones of the next cycle. Each cycle is 10-20 m thick. The whole section is placed into the Middle Siwaliks, with the local name of "Serie de Dharan Bazar". A regular cyclic sedimentation seems restricted to certain horizons within the Molasse-like Siwaliks, and has not been stressed by other authors.

From what is so far known of the Siwalik belt of Nepal, most, if not all of the sections are *normal.* Folding, imbrications and local thrusting do exist, generally dipping northwards and indicating a movement from north to south. From HAGEN's regional survey of the Siwalik belt it seems evident that in the eastern foothills, abnormal structures, some even north-south-directed, are present. Westwards, abnormal strike directions can be recognized as far as Namje west of the Sapt Kosi, where HAGEN discovered a NS-striking fault zone. From here further to the west, he stresses the conformable aspect of the foothill structures, running mostly parallel to the Main Boundary Fault. Some discrepancies occur again in the western foothills, where complications can be also noted in the Lower Himalayan Piuthan zone of HAGEN. Here the Siwaliks have their greatest width. Marked cross features are again visible towards the western border of Nepal. Some of the cross features, particularly of the eastern Siwalik belt may be related to the north-south-directed culmination of eastern Nepal, well expressed in the structural cross-high of the Arun River. The structures of the Siwaliks, running against the Main Boundary Fault, and the complications of some of the thrusted Lower Himalayan

features do indicate relief thrusting, a mechanism suggested by HAGEN for the Nepal Himalayas.

Most of the Siwaliks foothills disappear below the Ganges alluvium and the large Quaternary fans. Locally sub-Recent to Recent movements are still manifest in the form of locally thrusted Siwaliks over Quaternary terrace material (HAGEN, 1956, 1959), and by the progressive steepening of various terrace levels towards the Main Boundary Fault (BORDET, 1961). We will recognize the latter features even better expressed in the border foothills between Sikkim and Bhutan.

LOWER HIMALAYAS OF NEPAL

Like the Kumaon Himalayas, the Lower Himalayas in Nepal are morphologically well defined. Bordering the Siwalik Sub-Himalayas in the north and running parallel to the Main Boundary Fault is a conspicuous mountain range which does not fall below the 3000 m level in height. It is called the Mahabharat Lekh and can be followed from the Kali Gorge at the western Nepal border to the hills of Darjeeling in Sikkim. It is cut through by only the major rivers. In the north it is succeeded by the topographical depression in which lies the capital Kathmandu and the important town of Pokhara (Ph. 34). Beyond the Kathmandu Plain rise the Higher Himalayas along the Main Central Thrust.

In spite of various geological investigations, apart from the regional work of HAGEN, the complicated geology of the Lower Nepal Himalayas is still little understood. Here again it is mainly the lack of fossils, and therefore the missing stratigraphical control, as well as the metamorphism obeying yet little-understood rules, which leave so many unknowns in Nepal's geology. It is the merit of HAGEN's pioneer work that he distinguished in the Lower Nepal Himalayas two main geological and tectonic units: a lower *Nawakot-Piuthan* unit, predominantly sedimentary, and a higher *Kathmandu unit*, which is mostly crystalline. Each of these units is subdivided into several thrust sheets. The Kathmandu unit forms the base of the Higher Himalayas, but covers also large tracts of the Lower Himalayas. On very general lines HAGEN has compared the Navakot units to the Krol nappes of AUDEN, and the Kathmandu crystalline sheets with AUDEN's Gahrwal nappes (1937 a) or the Almora thrusts of HEIM and GANSSER (1939). HAGEN's detailed picture is, however, much more difficult to follow. According to him the Nawakot unit itself is subdivided into 4 nappes. The lowest, Nawakot I, is underlain by the parautochthonous window of Pokhara, which according to BORDET (1961) may after all not be such an independent element. To the west, the Nawakot nappes are replaced by two additional units, the parautochthonous Piuthan zone below, and the Jajarkot nappes above, the latter again subdivided into a lower and upper nappe. Towards Kumaon, additional tectonic elements, such as the Bajang nappes (with four local nappes) and the parautochthonous Dandeldura crystalline, which seems the direct continuation of the Almora thrust sheets in the west, complicate the picture still more. Whilst we accept the regional correlations with the Kumaon tectonic units, HAGEN's more detailed subdivisions of western Nepal do not fit as readily into the picture. The main problem consists, as clearly stated by BORDET, in the *unexpected multitude of nappes* in the Lower Himalayas as envisaged by HAGEN. In the west (eastern Kumaon), as well as in the eastern part of Nepal (BORDET and LOMBARD), the number of recognized thrust sheets is considerably smaller. The question arises whether the thrust elements in Nepal are subject to rapid lateral changes, or whether only parts of the stratigraphical section are involved, while to the west and east the thrust sheets embrace a more complete stratigraphical sequence. Unfortunately, we have so far no detailed stratigraphical descriptions of HAGEN's many nappes. Although only one definitely proven and determinable fossil locality in the Lower Himalayas (Silurian fauna of Pulchauki, Fig. 101) which lie on top of the Kathmandu nappes has so far been discovered, HAGEN (1959a) proposes the following stratigraphical section for his Nawakot nappes:

calcareous and polygenic breccia	= ? Rhaetic
dolomites	= ? Triassic
"Verruacano" conglomerates	= ? Permian
carbonaceous phyllites	= ? Carboniferous
sandstones	= ? Lower Palaeozoic
phyllites, micaschists and gneisses	= ? Precambrian

This sequence should be comparable with the section investigated by BORDET (1961) in the Lower Himalayas along the Kali Gandaki west of Pokhara:

thick section of arkosic Flysch-type sediments (Serie de Kuncha)	= ? Jurassic
yellow dolomites	= ? Triassic
"Verrucano"	= ? Permian
banded schists and white dolomites	= ? Carboniferous
dolomites with *Collenia*	= ? Devonian
black phyllites	= ? Silurian
granites	= ? Precambrian

Comparing these lithological sections with Lower Himalayan sediments further to the west as well as with the fossiliferous sections of the Tibetan or Tethys Himalayas, one doubts the ages assigned by both HAGEN and BORDET. Why should a Permian age be suggested for a conglomerate resembling the Alpine Permian Verrucano 6000 km away, while elsewhere in the Himalayas the Permian occurs in a calcareous shaly *Productus* facies? Strikingly Verrucano-like sediments have been found by the writer in southern Central Bhutan in an association recalling quartzitic Dalings, and probably of late Precambrian to Cambrian age. BORDET believes his *Collenia*-bearing dolomites to be of Devonian age. As we have already seen in the Kumaon Himalayas they are Cambrian or older, an age proven for very similar *Collenia*-bearing dolomites in the Middle East Elburz Range, where they occur in typical siliceous dolomites far below Middle Cambrian faunas.

Around Kathmandu and further to the east, the mostly crystalline Kathmandu nappe covers the Nawakot units of the Lower Himalayas. HAGEN distinguishes 5 different Kathmandu nappes, of which the upper one is involved in the Higher Himalayas—HAGEN's "root zone".

For some unknown reason, a remnant of sediments overlying the Kathmandu nappe southwest of Kathmandu on the Pulchauki Hill in the Mahabharat Range, has escaped the regional metamorphism. Here SUTTON BOWMAN discovered for the first time determinable fossils after MEDLICOTT (1875) had collected some indeterminable crinoids in the same region. AUDEN studied these outcrops in more detail and gives an Ordovician age to his collected fauna. Later HAGEN with B. P. MALLA found Silurian trilobites (1959), which was confirmed by further collections by BORDET (BORDET et al, 1959). This seems so far the only determinable fossil locality in the Nepalese Lower Himalayas. The geological situation of the Pulchauki Ridge is given by BORDET (Fig. 101). The relation of the unmetamorphic shales and quartzites with the underlying gneisses of the Kathmandu thrust sheet is not clear. BORDET believes that the contact is tectonic and that the sediments are detached from the underlying gneisses. A generalized section has been published by AUDEN (1935), reproduced as Fig. 102. This section does not conform with HAGEN's profile No. 30 (1959 a).

In eastern Nepal, the Lower Himalayas have been traversed by LOMBARD during the first Swiss Everest expedition in 1952 and again by BORDET and later BORDET and LATREILLE during the French Makalu expedition (1954 and 1955). The same area was also included in the regional surveys of HAGEN. Preliminary results were known from AUDEN's traverses in the Arun and Tamur Rivers. With his great Himalayan experience AUDEN recognized the general structural outline. He stressed the widespread gneiss thrusts, reminiscent of the Darjeeling gneisses overlying vast extenses of Dalings. He also recognized the E-W striking thrusts in the Kathmandu region and drew attention to the remarkable cross features in the Arun and Tamur Valleys and compares them with the cross structure of Sikkim. AUDEN was already well aware of the major problems of the Himalayan crystalline thrust sheets. He noticed that no sharp boundary exists between the Darjeeling-type gneisses and the underlying

Phot. 33 *The famous Kailas (6700 m)* built by thick-bedded conglomerates transgressing onto the Kailas granite, outcropping in the two hills to the right and left of Kailas. Local moraines in foreground. View towards S (phot. A. Gansser)

Phot. 34 *The terraced plain of Pokhara* with the front of the Higher Himalayas. Main thrust passes below present snow line. View towards N. 1 = Machapuchare (6997 m), 2 = Annapurna III (7577 m), 3 = Annapurna II (7937 m) (phot. F. Müller, copyright Swiss Found. Alp. Res.)

Phot. 35 *The Machapuchare* (6997 m), with its impressive, well-bedded gneiss section above the central main thrust, dipping to the north. View towards the NE (phot. B. R. Goodfellow)

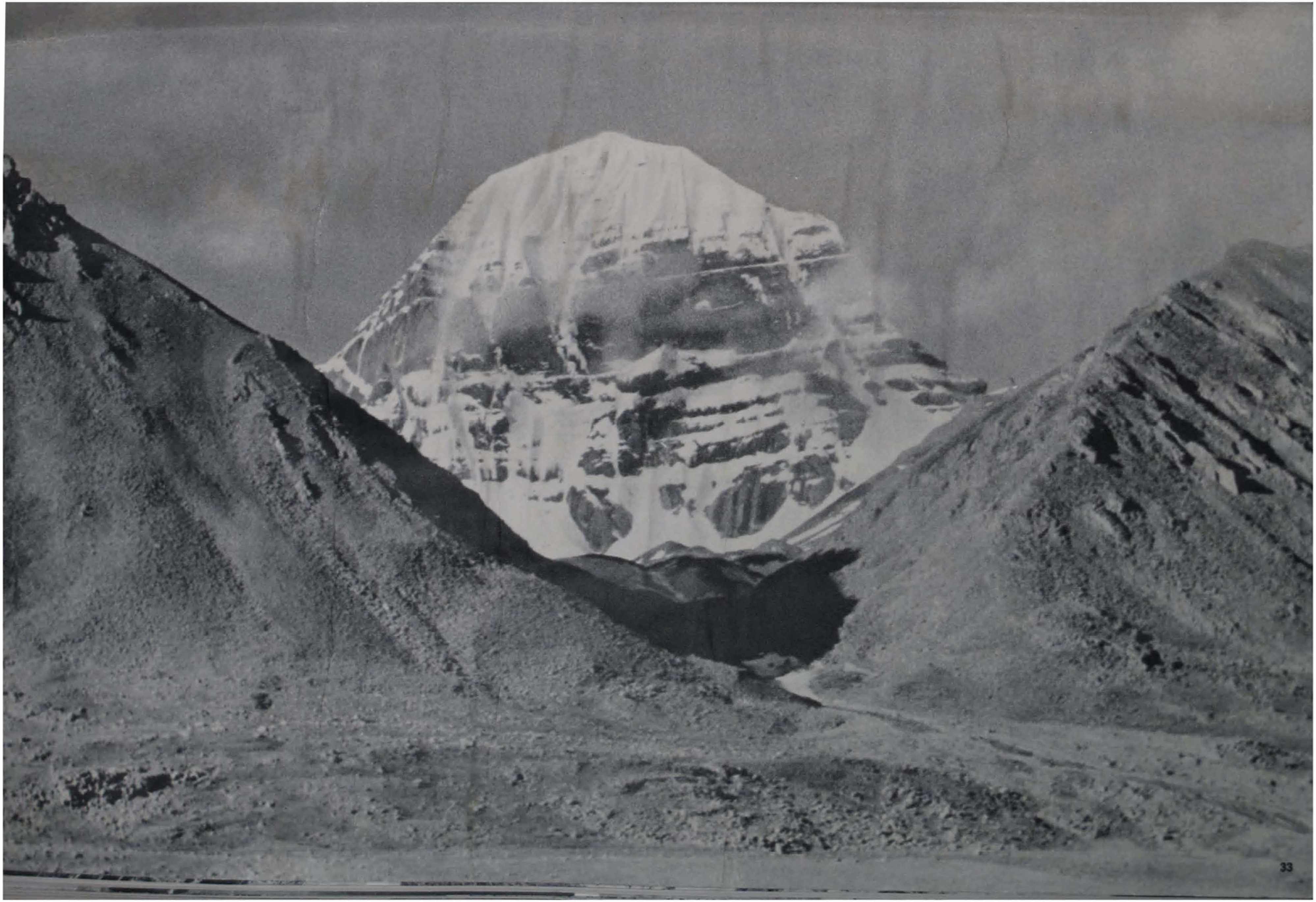
Phot. 36 *The Daulagiri* (8222 m) NNE face, exposing the excellently bedded calcschists and quartzitic calcareous phyllites of the Tukucha formation (phot. N. Dyhrenfurth)

Phot. 37 *Banded migmatites cut by younger tourmaline granite dykes.* Block derived from the base of Pumori. It resembles the migmatites of Namche Bazar (Everest region, phot. A. Lombard)

Phot. 38 *Tourmaline granite intrusion of Makalu type into banded biotite-gneisses.* Khumbu glacier (Everest region, phot. A. Lombard)

Phot. 39 *The west side of Everest,* with Khumbu Glacier. 1 = Changtse (7547 m), capped by north dipping Everest limestones. 2 = Everest (8848 m) with carbonate rocks on the summit (light coloured) and pelitic series underneath (dark colour). In front the West Shoulder (7184 m) consists of Makalu granite intruding the higher pelites. 3 = Lhotse (8501 m) with dark pelites, 4 = Nuptse (7827 m). Foreground: remnants of black gneisses in granite (phot. N. Dyhrenfurth; copyright Swiss Found. Alp. Res.)

Phot. 40 *The southwest face of Everest and Nuptse.* Khumbu Glacier in foreground. Calcarous sediments of the Everest summit (1) overlying dark pelitic series. Intrusions of Makalu granite into pelitic series above the West Shoulder. Nuptse (2) with base of migmatites and "black gneisses" (lower right) covered by a large body of Makalu granite with dark pelites, forming the very summit with local folds. Regional dip to N (phot. N. Dyhrenfurth; copyright Swiss Found. Alp. Res.)



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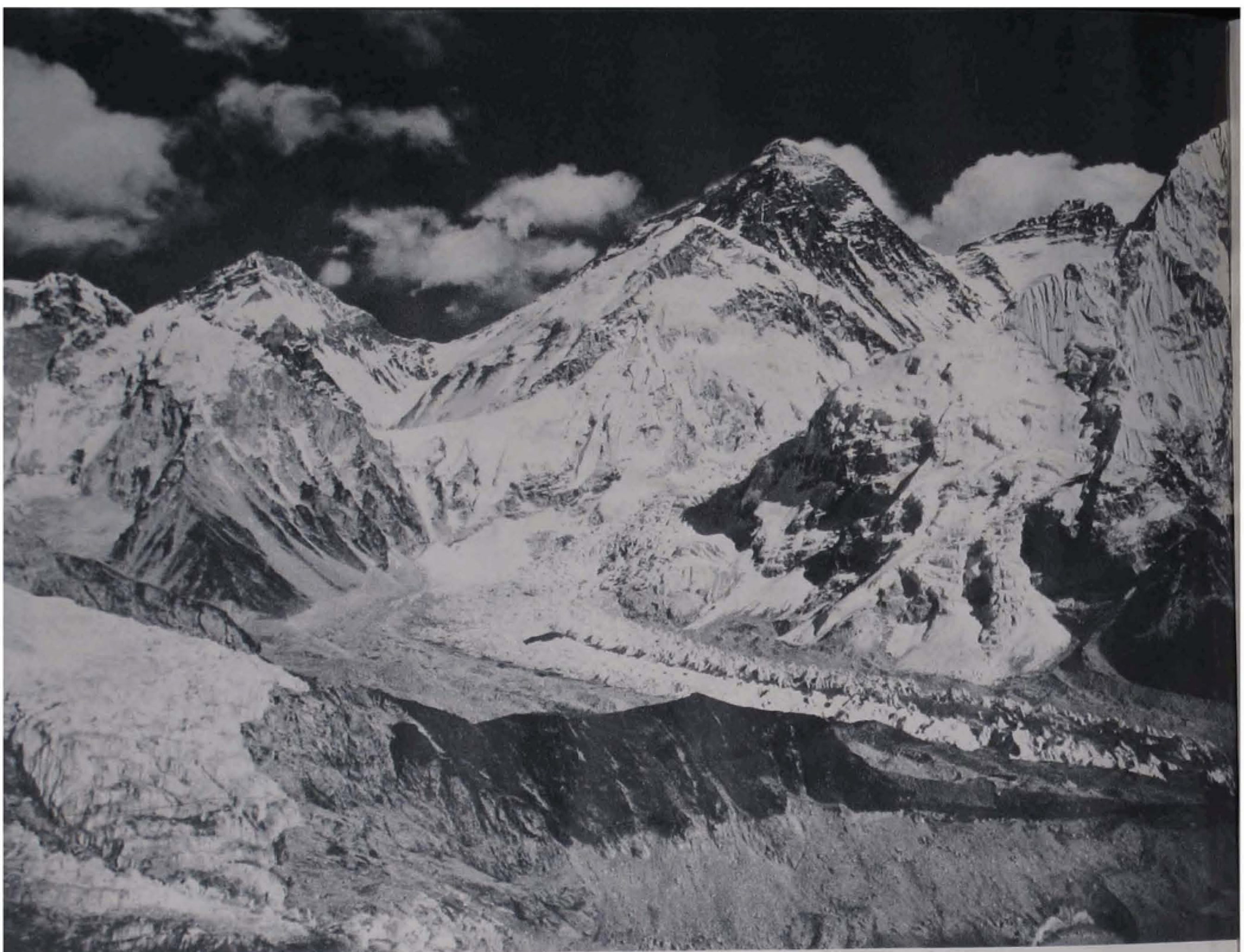

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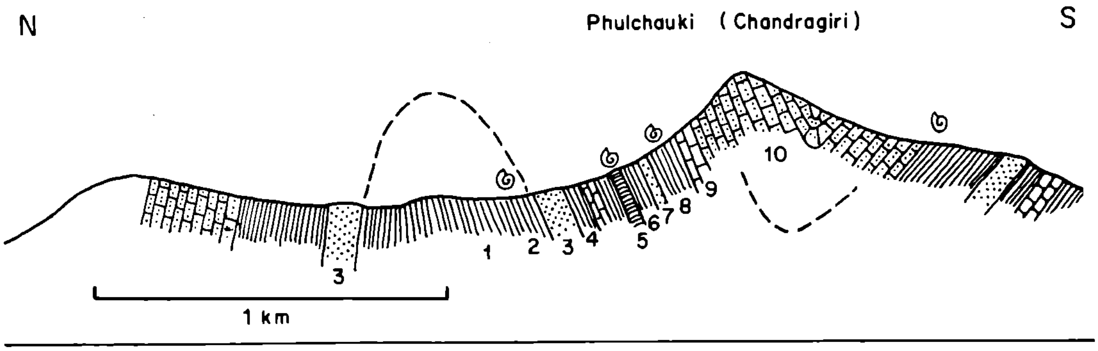


Fig. 101 *Section across the Pulchauki ridge,* south central Nepal; redrawn after P. BORDET (1961)

1 grey shales
2 greywacke with Brachiopods
3 quartzites
4 green and reddish shales with calcareous layers
5 hematitic horizons with Trilobites
6 grey shales
7 quartzites
8 greywacke with Trilobites and Brachiopods
9 Godavari marbles with Crinoids and Orthoceratids
10 thick dolomites

Daling slates. The metamorphism increases gradually from epi-, meso- to kata-metamorphic grades, and AUDEN compares these facts with the well-displayed and well-known features in Sikkim. Though as yet little understood (see later), this regional behaviour is of great importance, but has not always been taken into consideration by later explorers of Nepal.

For the eastern part of the Nepalese Lower Himalayas, LOMBARD (1958) has introduced a new structural element, the crystalline Khumbu nappe, corresponding to HAGEN's Kathmandu nappe No. 5. HAGEN, accepting the Khumbu nappe, divides it into three nappes, and the upper one, Khumbu 3, again into three units which develop east of the Arun River into the Lumbasumba nappe and the overlying Kangchendzönga nappe.

The lower Khumbu nappes reach the foothills of eastern Nepal at Dharan, and continue into the Darjeeling gneisses. HAGEN's prolific constructions of nappes is not easy to understand, considering the important problem, already stressed by AUDEN, of the gradual upwards increase of metamorphism so that any tracing of a thrust line will be most difficult. Here, as in western and central Nepal, we miss the stratigraphical-lithological control to verify and correlate the tectonic subdivisions. Until more detailed descriptions are available, we can neither accept nor disprove HAGEN's tectonic picture. We have already seen in western Nepal that correlations are only possible on very broad lines, since the various authors do not agree on the details. This fact is best illustrated by comparing the three sections from Everest to the Ganges Plain prepared by HAGEN, LOMBARD and BORDET, Fig. 103a, b, c (HAGEN, 1959 a, Profile 14; LOMBARD, 1958, Pl. II; BORDET, 1961, Fig. 6).

For the Lower Himalayas of eastern Nepal we follow for the time being the latest results of BORDET and LOMBARD, with HAGEN's in-

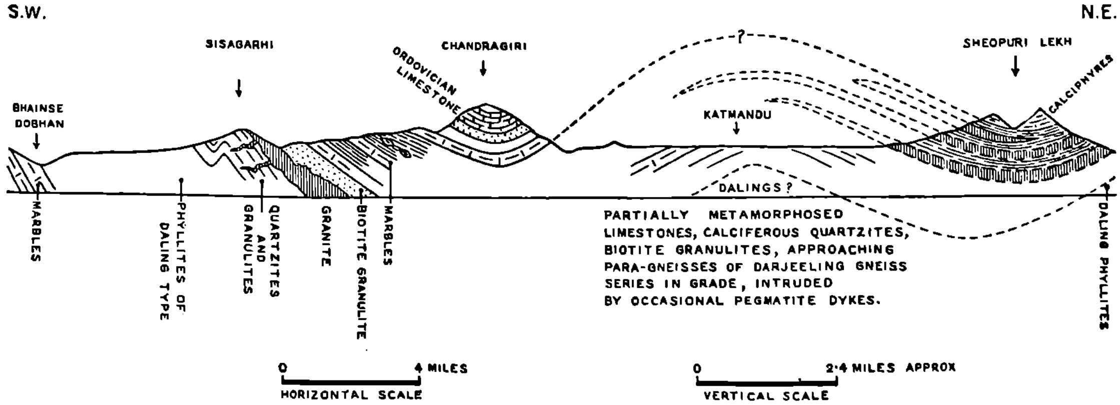


Fig. 102 *Generalized section across central Nepal.* Nepal Lower Himalayas; reproduced from J. B. AUDEN (1935)

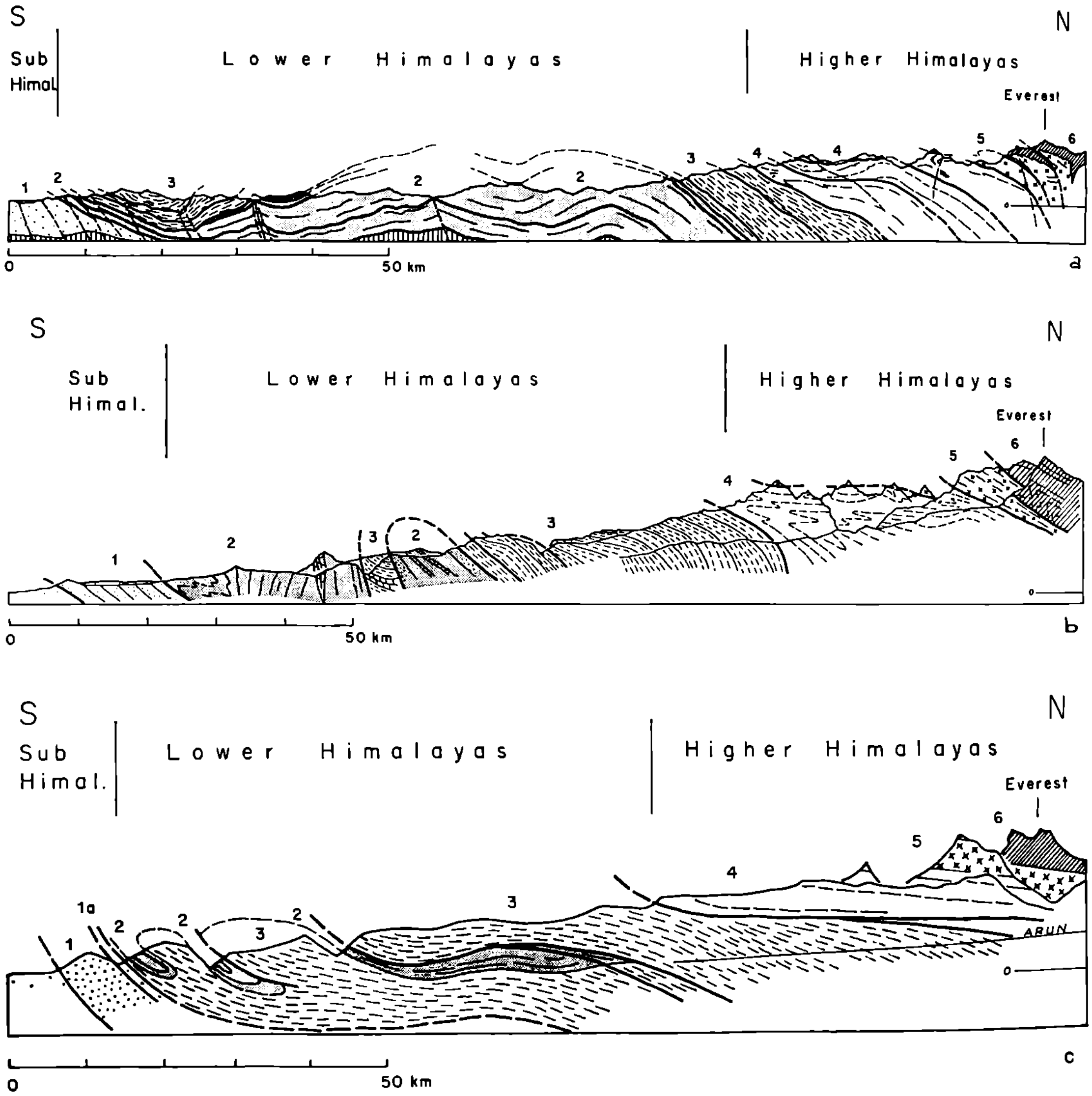


Fig. 103a, b, c *The cross sections from Everest to the Siwaliks, a comparison;* a after T. HAGEN (1959), b after A. LOMBARD (1958), c after P. BORDET (1961) all sections are reduced to same scale. Sections b and c have slightly exagerated heights

1 Siwaliks
1a Sanguri (BORDET)
2 Nawakot nappes (serie de couverture, BORDET)
3 Kathmandu nappes (migmatites of Lower Himalaya, BORDET)
4 Khumbu nappes
5 Makalu granite
6 Tibetan zone, Everest

vestigations incorporated as far as possible. BORDET distinguishes just north of the Main Boundary Fault the Sanguri Series, followed by his Lower Himalaya unit. The Sanguri section begins with over 1000 m of phyllites, from bluish grey to greenish and reddish in the upper horizons. Locally, some reddish violet, probably pyroclastic zones are recognized. In the Upper Sanguri section quartzites dominate; they are thick-bedded, mostly white, pinkish and yellow and locally contain some white quartz pebbles. Ripple marks are preserved on the bedding planes and a weak copper mineralization seems fairly widespread. The whole section is often intensely folded, forming narrow southwards-overlying synclines. Folding and local thrusting is particularly strong below the thrust of the next unit—BORDET's ensemble of the Lower Himalayas. The Sanguri section could be compared to the Nawakot nappes of HAGEN, but resembles rather the Daling of AUDEN and is unlike his Krol sections. In the region of Dharan, this section becomes

strongly reduced, and disappears altogether towards the east.

Along the lower gorge of the Kosi River, further to the west, AUDEN and DUTTA discovered in 1946 Gondwana-type Damuda rocks. They reported highly folded siliceous dolomites underlain by coal-bearing sandstones containing a boulder bed of glacial origin. The boulders consist of angular to rounded limestones, slates, white quartzites and some granite gneisses, and are embedded in the characteristic badly sorted dark-brown silty matrix, which, being strongly sheared, has become slaty. The coals are just as strongly sheared and are reported to be devoid of spores and larger plant remains. They resemble the sheared coals of the Darjeeling district. AUDEN compares the boulder bed-dolomite sequence with the rocks of the Krol belt (JACOB, 1952). It seems unlikely that these Gondwana sediments belong to the Sanguri section of BORDET. They may form a tectonic wedge between the Main Boundary Fault and the latter.

The Lower Himalayan Unit of Bordet has been subdivided into 7 lithological items, which, according to their author, constitute a normal stratigraphical sequence. This relatively simple synthesis of a structurally most complex sequence is the great merit of the careful analysis of BORDET, but only further investigations will show how far these subdivisions can regionally be accepted. They are certainly most important for the better understanding of the general tectonics.

1. *The migmatites*, in the widest sense, cover the greatest part of the Lower Himalayas of eastern Nepal. BORDET applies this term rather freely and includes all varieties of granitized schists. Frequent rock types are quartzitic biotite-sericite gneisses, platy two-mica gneisses rich in garnet, kyanite and large muscovite on the bedding planes, and augen gneisses with fist-size phenocrysts. These gneissic masses can be several thousand metres thick and are traversed by amphibolitic dykes as well as aplites and pegmatites. Certain tourmaline pegmatites may be related to the youngest granitization.

2. *Mica schists* cover the migmatitic gneisses. They contain frequent garnets, staurolite and kyanite and often large muscovites. The border against the gneisses is not sharp, and frequently the latter develop from the schists by granitization. This fact leaves some doubt if the schists should be placed stratigraphically above the gneisses as suggested by BORDET, or, which may be more likely, are in fact older. Contacts against highly granitized gneisses are sharp.

3. *The lower quartzites* are characteristically fine-bedded and rich in biotite. Often a varve-like banding in white and grey is visible. Less frequent are garnet and some kyanite on the bedding planes. Intercalated marble bands are generally associated with amphibolites. They have rarely been observed in outcrops, but may form important key beds. The maximum thickness amounts to 500 m in the Barun Valley.

4. *The lower phyllites* form a 300-400 m thick zone above the lower quartzites. Generally greyish-blue to greenish, they contain sericitic horizons with idiomorphic garnets, staurolite and kyanite. Intercalated in the phyllitic parts are rusty weathered graphitic schists which locally can contain nearly pure graphite. Generally they occur in the upper part of the phyllitic zone.

5. *The upper quartzites* are thinner than the lower ones and can be distinguished by the lack of biotite and their slightly greenish colour caused by chlorite. They are not more than 100 m thick, and form a most constant horizon.

6. *The calc-schists and upper phyllites* represent the highest horizons observed. Within yellowish and reddish phyllites occur sacharoidal marbles rich in white grammatite and actinolite, in sphaerolitic arrangements. Upwards the phyllites increase, becoming more bluish grey and silky. They are practically free from garnets. Altogether 400-500 m of phyllites and calc-schists are exposed.

7. *The Salung conglomerate.* In the western continuation of BORDET's Lower Himalaya, LOMBARD has observed a section which seems to be missing in the more eastern area, but may develop from the highest section of BORDET, above the upper phyllites. In a schistose micaceous sandstone which LOMBARD compares to some flyschy deposits, there are conglomeratic horizons with polygenic components in a sericitic groundmass. This clastic zone is unfortunately not described in greater detail. BORDET prefers a possible correlation with the Blainis, so far unknown in this part of the Himalayas, except for the Gondwana rocks mentioned from the Kosi River gorge of the foothills. A tentative age has been assigned by BORDET to the sections already mentioned. They are supposed to range from the Precambrian to the Permian, but not a single fossil has so far been found to prove this interpretation. The following list proposed by BORDET is based only on lithological correlations with neighbouring regions:

Salung Conglomerate	= Permian
Upper Phyllites (with calcareous zone)	= Carboniferous
Upper Phyllites with carbonates	= Devonian
Upper Quartzites	= Silurian-Devonian
Lower Phyllites	= Silurian
Lower Quartzites	= Cambro-Silurian
schists and gneisses	= Precambrian

Though the lithological subdivisions make sense, the writer, from his own experience, doubts the value of such tentative stratigraphical interpretations.

The section of the Lower Himalayas is complicated by severe folding and thrusting. BORDET distinguishes major anticlinal features, all of them included in his main thrust sheet of Barunse. This is covered by the next, higher thrust mass of Tinjure, which consists predominantly of schists and gneisses. Northwards, this mass is bordered by the main thrust of the Higher Himalayas. A remarkable feature is the *north-south directed cross folding*, excellently expressed in the large northwards-directed domal uplift along the Arun River. This cross feature, well-outlined in the Lower Himalayas, continues into the Higher Himalayas, and is cut by a north-south running fault line (Fig. 104 and general map, Pl. I).

HIGHER HIMALAYAS OF NEPAL

Of the 14 mountains over 8000 m high in the world, 9 belong to the Higher Himalayas of Nepal. Only Kangchendzönga, Makalu and Cho Oyu do not quite reach into the Tibetan sediments, while the rest, including Everest, are capped by, or just touch the base of the Tibetan marine deposits.

The Lower Himalayas and Higher Himalayas of Nepal are divided, as are the Kumaon Himalayas, by a major thrust zone. Below this thrust zone we have the complicated structures of the Lower Himalayas, with normal and reversed sections, while above the main thrust *a huge normal sequence* begins, forming the base of the Tibetan sediments —the Tethys-type deposits.

The major thrust falls within the Katmandu nappes of HAGEN. From his multitude of tectonic profiles crossing from the Gangetic plains to

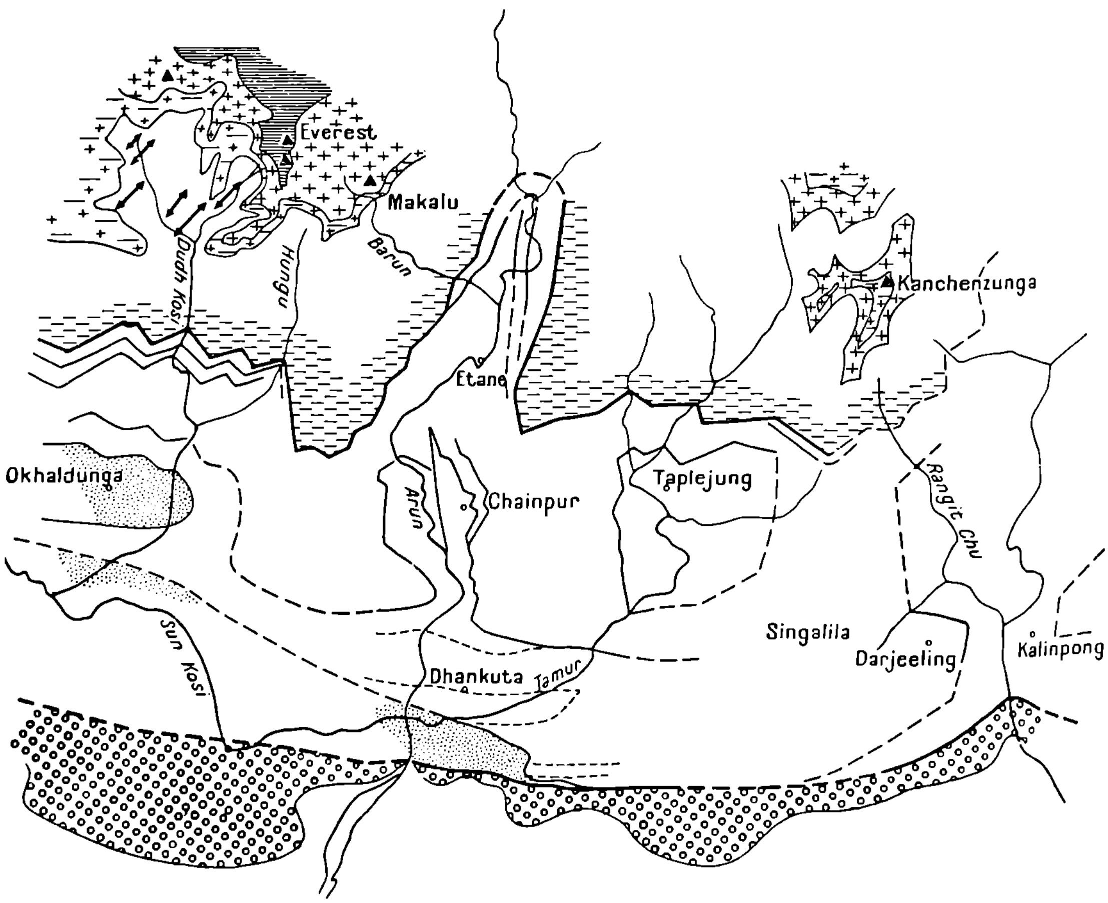


Fig. 104 *Schematic geological sketch-map of E Nepal.* Reproduced from P. BORDET (1961)

circles = Siwaliks
dots = Nawakot
white = Katmandu (Lower Himalayas)
dashed = Barun gneiss (Higher Himalayas)
cross and dash = injection zone
crosses = Makalu granite
lined = Everest series

Tibet (Nos. 2-86 mentioned in HAGEN, 1959 a, but not all published yet) it seems to be his nappe Katmandu No. 5 (in the E, after LOMBARD, called Khumbu nappe) which forms the normal base of the Higher Himalayas.

The Higher Himalayas have been called by HAGEN the "root zone" of his crystalline nappes. This term, borrowed from the Alps, does not seem applicable in its restriced sense to the Higher Himalayas. It would be difficult to restrict this so-called root zone to the southern belt, and by this terminology the whole range would correspond to a root zone. It has not been applied by BORDET for the Higher Nepal Himalayas.

The two sections through the extended chain of the Nepalese Higher Himalayas which are best documented and therefore of greatest interest, are those through the Kali Gandaki in the west and the Everest region in the east.

Kali Gandaki section

Geologically this section is probably the best frequented part of Nepal's Higher Himalayas. The most recent results date from the explorations by EGELER and DE BOY in 1962, FUCHS 1963 and at present BORDET with REYMAND and KRUMMENACHER is visiting this area again. Apart from HAGEN's publication (1959 b), BORDET has given a short account of his results obtained during a visit in 1956-57. While writing the present text, the author has received a manuscript by EGELER and coworkers on the preliminary results of their 1962 expedition into Central West Nepal, covering in particular the upper Kali Gandaki section. The author greatly appreciates the permission to use some of the information (EGELER et al, 1964, in preparation).

We have already referred to BORDET's thick Flysch-type section of Kuncha in the middle Kali Gandaki. These monotonous deposits dip rather gently to the north and are overlain with a thrust contact by a schuppen zone of greenish phyllites with some quartzites and dolomites. They form the base of the major crystalline thrust of the Higher Himalayas. EGELER stresses the frequent occurence of amphibolites at Tatopani, bordering the southern quartzite section towards the schuppen zone of BORDET.

At Dana one crosses the *main thrust*, manifest as a schistose mylonite zone underlying a thick section of banded biotite gneisses, hornblende-garnet gneisses with carbonate zones and, higher up, augen gneisses cut by younger tourmaline pegmatites. Typical granitic rocks have not been observed. According to EGELER, the basal crystalline thrust sheet can be divided into a lower part, characterized by garnetiferous plagioclase gneisses with some local marble bands, and a higher part with microcline gneisses of granitic origin. HAGEN reports biotite-tourmaline granite gneisses near the upper contact. The total thickness of this crystalline thrust sheet amounts to over 10 km, but imbrication and isoclinal folding are not excluded. EGELER, contrary to HAGEN's interpretation, regards this crystalline mass as one major thrust sheet. This is in line with our conception of the adjoining areas (Ph. 35).

At Dhumpu the upper contact is of particular interest. Here, in contrast to the Kumaon Himalayas, we miss the normal decrease in metamorphism of the argillaceous part of the Precambrian-Cambrian sections, which develop gradually from the underlying gneisses. BORDET suggests a tectonic contact between the uppermost gneisses and the first sediments—micaceous sacharoidal limestones of presumed Devonian age. HAGEN mentions crystalline limestones, partly with lime silicates and assigns to them a Silurian-Devonian age. EGELER also reports a sharp contact at Dhumpu, but thinks that this contact might correspond to a masked unconformity rather than to a tectonic accident. He distinguishes a section of about 2200 m of marbles with schistose amphibole gneisses grading into more calcareous biotite schists and impure marbles. They are isoclinally folded and are overlain by a conspicuous carbonate group which forms the central body of Daulagiri and the summit of Nilgiri, after which this limestone section has been named by EGELER. This upper calcareous formation is about 1600 m thick and consists of well-bedded limestones with argillaceous intercalations. Towards the top the limestones become more massive and dolomitic. Intercalated siltstones show current bedding. The limestone section is less metamorphosed than the underlying gneisses and schists, and the tectonic disturbances have decreased. EGELER suggests that the underlying metamorphics are still of Precambrian age and places the limestones into the lowest Palaeozoic, since they contain badly preserved gastropods and crinoids and are overlain by Lower Silurian formations, which will be discussed in a later chapter (Fig. 105).

HAGEN mentions a thick section of phyllitic limestones in the Tukucha Basin which can be followed into the summits of Daulagiri and Annapurna. It seems that at least a part of HAGEN's Tukucha formation is made up by the Nilgiri limestones of EGELER. One of HAGEN's Daulagiri samples, kindly placed at our disposal, consists of a fine-grained, grey, phyllitic calc schist. The calcites are elogated parallel to the schistosity, together with some sericite flakes. Detrital, rounded quartz and acid plagioclases are locally enriched in layers, together with some tourmaline grains. The well-bedded rock shows an intense subfolding in the centimetre dimension. This

calc schist is surprisingly similar to the grey calc schists forming the summit ridge of Everest.

The pronounced banding of the Tukucha formation is clearly visible in all the pictures published of the 8222 m high Daulagiri (Ph. 36). It is also excellently displayed in HAGEN's beautiful picture of Annapurna (HAGEN, 1956 b). The visible structural uniformity, emphasized by this unique banding of the Higher Himalayas, contrasts however with HAGEN's tectonic profiles (1959 a).

Everest section

The first geological exploration of the Everest region was carried out from the north, in line with the northern, Tibetan, approach of the climbing expeditions prior to the opening of Nepal in 1949. HERON (1922) describes the results from the first reconnaissance expedition as well as from the first attack. The investigations covering the Tibetan sediments will be discussed in the chapter dealing with the northern regions of Sikkim. It is surprising that at the first attack samples were collected up to a height of 8200 m, giving for the first time proof of the sedimentary composition of the upper horizons on Everest. HERON describes dark greenish banded hornfelses, foliated calc-silicate schists, and whitish platy crystalline limestones. ODELL has collected a wealth of information on subsequent expeditions (1924, 1938), but unfortunately most of his samples were stolen in 1939 and his respective notes and maps destroyed in 1941, including all the work done in the last fourteen years. WAGER, who participated in the 1933 Everest expedition has contributed additional information and discussed also the unexpected cross cut of the Arun Gorge (1934, 1937). His observations dealing with the Lachi Series of northern Sikkim (1939) will be dealt with in the chapter on Sikkim. In the same publication he also discussed the age of the Everest limestone, and correlated it with the Baxas, placing it into the Permo-Carboniferous.

LOMBARD, accompanying the Swiss Everest expedition in 1952, was the first geologist to visit the southern side of Everest. He was followed by BORDET in 1954 and BORDET with LATREILLE in 1955. At the same time the southern Everest region was also investigated by HAGEN. BORDET (1961) has given an excellent compilation of the various results, including the observations of FREULON during the Jannu expedition in 1959.

Following BORDET, the Higher Himalayas in eastern Nepal can be regionally subdivided into three major units (Fig. 111):

1. Barun gneisses
2. Makalu granites
3. Everest sediments.

Barun gneisses

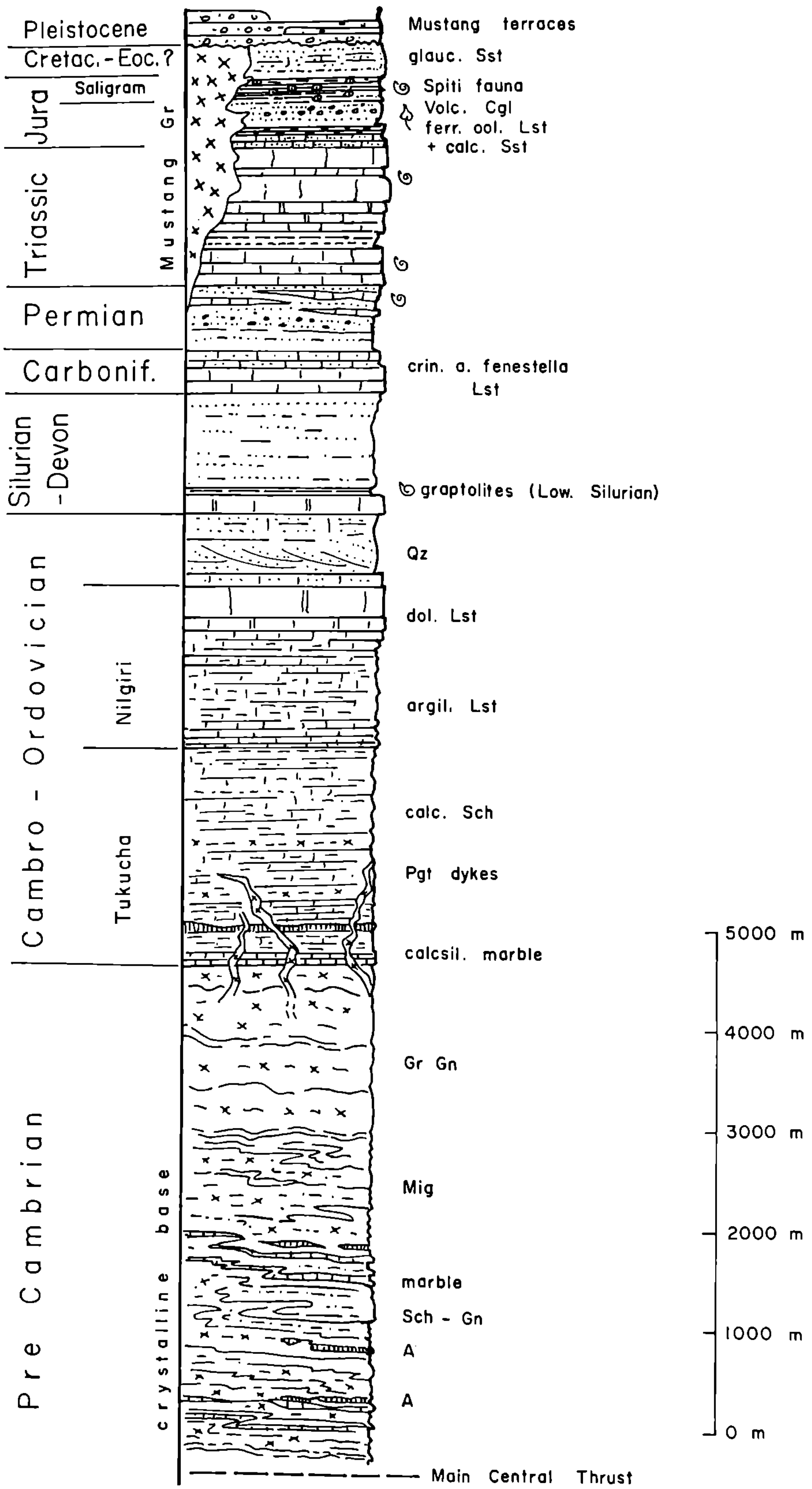
Conformable with sections already described in the Kumaon Himalayas and Kali Gandaki of western Nepal, the Barun gneisses form the crystalline base of the normal unit leading upwards to the sedimentary section of the Tethys or Tibetan Himalayas. In this very thick crystalline sheet, BORDET distinguished a lower ectinitic gneiss, followed by the Barun migmatites and the black gneisses. The lower gneisses are high-grade metamorphic with sillimanite and garnet. Their banding is fine, feldspar-rich layers alternating with dark biotite bands. Muscovite is missing. Layers rich in sillimanite form local gliding horizons, a fact the author noted in similar gneisses in Bhutan. Locally kyanite was found. In some horizons, a surprising growth of certain minerals has been observed. BORDET mentions idiomorphic garnets up to 15 cm and xenomorphic types over 20 cm. The usually fine-grained feldspars can increase to form augen gneiss and certain augen attain a size of 8-10 cm. In the lower part of this section amphibolites occur, often garnetiferous, accompanied by bluish marble layers, some characterized by diopside.

The lower Barun gneisses generally have gentle regional dips, in spite of some sharp internal folding, and form enormous cliffs (Fig. 106). Their intense banding, alternations of various composition and particularly the inclusion of marbles, suggest a thick altered sedimentary section. The whole is traversed by some white tourmaline-garnet-aplite veins, which either cut through the layers, or more frequently conform to the bedding.

The base of the Barun gneisses is in tectonic contact with the crystalline thrust sheet of Tinjure of the Lower Himalayas. The contact is complicated in some sections by the introduction of secondary thrust sheets, forming a kind of schuppen zone at the base of the Barun gneisses. Most of these schuppen consist of gneisses with a cover of biotite quartzites, often over 500 m thick and topped by thin marbles. Apparently some of the schuppen seem to be reversed. Here, as in many other parts of the crystalline contacts, a post tectonic recrystallization often masks the original tectonic disturbance. (Fig. 104).

The Barun migmatites develop gradually from the underlying gneisses by an increase in larger feldspars, disappearance of the garnets and gradually increasing mobilization, witnessed by diffuse pegmatitic zones. The actual migmatites are only 500 m thick in the Barun Valley, but increase to 1500 m further east. Westwards, they can be

Fig. 105 *Stratigraphy of the Thakkhola area.* North Central Nepal; compiled after T. HAGEN (1959), P. BORDET (1961) and C. G. EGELER et al (1964)


Pleistocene
Cretac.-Eoc.?
Jura
Saligram
Triassic
Mustang Gr
Permian
Carbonif.
Silurian -Devon
Cambro - Ordovician
Nilgiri
Tukucha
Pre Cambrian
crystalline base
Mustang terraces
glauc. Sst
Spiti fauna
Volc. Cgl
ferr. ool. Lst
+ calc. Sst
crin. a. fenestella Lst
graptolites (Low. Silurian)
Qz
dol. Lst
argil. Lst
calc. Sch
Pgt dykes
calcsil. marble
Gr Gn
Mig
marble
Sch - Gn
A
A
Main Central Thrust
5000 m
4000 m
3000 m
2000 m
1000 m
0 m

correlated with the widespread migmatites of Namche Bazar, described by LOMBARD (1958) and KRUMMENACHER (1956) (Ph. 37).

The migmatites grade into the characteristic *black gneisses*, forming the base of the high summits of the Everest group. They are separated by the large Makalu granite sills from the higher dark Everest formations, with which they seem otherwise to form one continuous unit with decreasing metamorphism—a fact stressed by BORDET but contested by LOMBARD. The black gneisses are very fine grained, well bedded and banded and extremely rich in the biotite responsible for the dark colour. Locally layers of garnet-amphibolite are intercalated and, curiously, certain zones with larger quartz augen associated with violet cordierites. They may represent contact products of the underlying migmatitic veins or the influence of the higher intrusive Makalu granite. The black gneisses measure from 1500 to 2000 m.

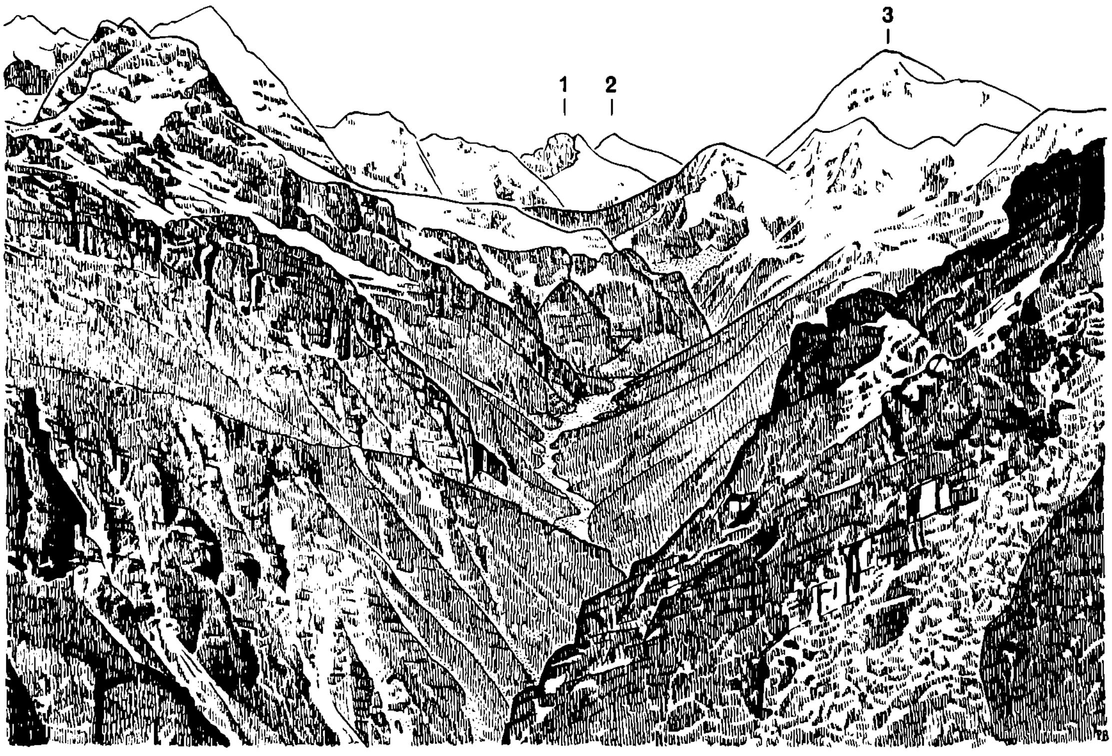


Fig. 106 *The Barun Valley,* view towards NW, reproduced from P. BORDET (1961); note the thick-bedded Barun gneisses

1 Lhotse 2 Everest 3 Makalu

Makalu granite

Following BORDET, the Makalu granite is a *post orogenic intrusion* set into a zone of possible differential movement between the lower Barun gneisses and the higher Everest pelitic formations. At both the base and the top, the granites are welded to the bordering formations by an intricate network of dykes and apophyses, which have not been affected by subsequent tectonic movements (Ph. 38). This fact is in favour of BORDET's suggestion, and, according to the author, it is in line with the behaviour of many other post-orogenic granites, so characteristic for the Himalayan range.

The granite is generally fine-grained, strikingly white, with biotite and or muscovite and tourmaline. The needle-like tourmalines can form large sheaves, surrounded by a white feldspar border. Plagioclases in the form of oligoclase dominate over the orthoclase. They can be idiomorphic, especially in the types rich in muscovite. The granite is completely massive but can break along a wide-meshed parallel cleavage system with no apparent relations to the tectonic trends. Upper as well as lower contact of the granite with the surrounding rocks is generally sharp (Ph. 38). Often the border is pegmatitic and muscovite-pegmatite can enter the border rocks, but on the other hand pegmatitic material can be enriched in the bordering granite with strikingly sheaf and palm-like arrangements of muscovites, a fact observed by the author also in post orogenic Alpine aplite granites (Novate granite

south of Chiavenna). Apart from the pegmatite and aplites, a most complex system of granitic apophyses and dykes can intrude the adjacent gneisses. The contact zone can assume considerable dimensions, surpassing even the size of the main granitic sill. This is particularly the case in the lower contact zones. In the Makalu we note 1500 to 2000 m of dyke intrusions, compared to 2000 m of granite (Fig. 107). Also, further to the NW, in the upper Khumbu Glacier, a thick granite is still present in the Nuptse (and the base of Everest) (Ph. 39, 40), while in the Pumori to the west, over 3000 m of dyke intrusions are exposed with a much reduced granite (Ph. 41). It is uncertain if the massive granites reach further to the northwest; northwards they are covered by the sediments of the Everest zone. To the northeast, from the eastern base of Everest to the Tibetan mountains north of Makalu, the granite is widespread and of considerable thickness, but it decreases southwards and wedges out. In spite of the variable thickness of the Makalu granite, the thickness of the underlying lower black gneisses and of the overlying Everest formations remains more or less constant. BORDET is therefore convinced that the granite is intrusive into an already metamorphosed, folded and faulted rock suite. This is well visible for instance in the Cho Polu west of the upper Barun Glacier (Fig. 108). Based on all the evidence, a young Tertiary age is thus assumed for the Makalu granite, an age already suggested by ODELL (1948).

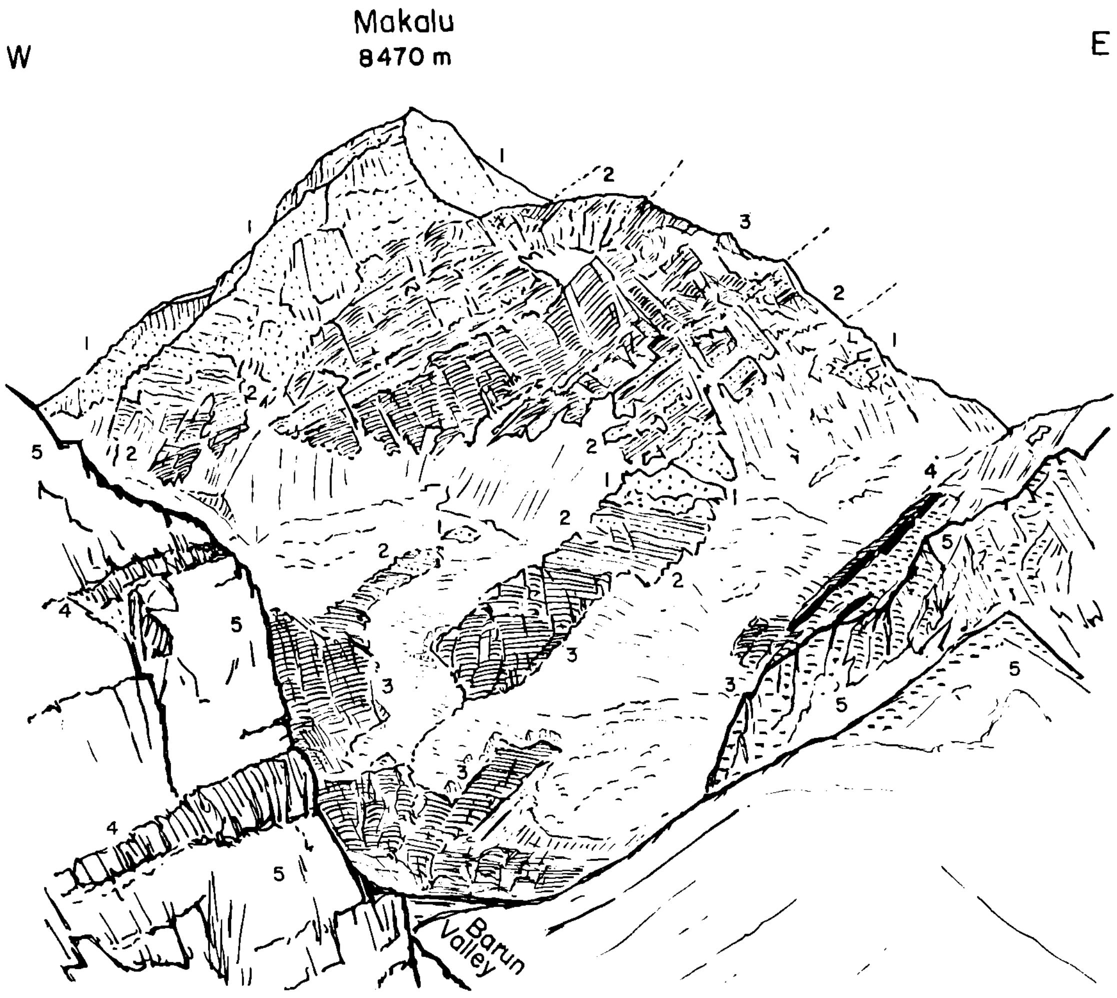


Fig. 107 *The Makalu with its granite intrusions;* drawn after photo by Ch. EVANS (Berge der Welt, 1955), geology after P. BORDET (1961)

1 Makalu granite 2 injection zone 3 black gneisses 4 amphibolites 5 Barun gneisses

Everest sediments

Above the Makalu granite the base of the Everest section shows the same black to dark green fine-grained gneisses that we have noted on the top of the lower black Barun gneisses, and this fact seems to suggest the *continuity of the section in spite of the Makalu granite intrusion.* Upwards, the gneisses pass gradually into black biotite schists and phyllites and finally into dark green pelitic rocks. With the gradual decrease of the metamorphism one notes a decrease in dyke intrusions connected with the Makalu granite and also a decrease in structural complications. Finally, towards the summit of Everest, the bedding becomes regionally uniform. Up to now we have had no direct information on the Everest sediments from the south side, since relatively few samples have been collected from the moraines or by climbing parties without geologists. On the other hand, the expeditions attempting Everest from the north had geologists in their attack groups reaching heights above 8000 m. In 1924 ODELL, on the same day that MALLORY and IRVINE vanished, climbed to 8200 m in excellent conditions and was able to do geological work. He was the first to confirm *that limestones form the summit of Everest.* WAGER, in 1933 as a member of the assault party, reached a height of 8570 m. Both geologists were able to give detailed first hand accounts of the calcareous slabby sediments, dipping gently to the north, most unfortunately for the northern climbing parties. The gentle north dips of the sediments bring the respective layers down northwards into the Rongbuk Valley in Tibet, where, at the snout of the Rongbuk Glacier, the formations were studied in more detail. We follow WAGER (1939) in subdividing the sediments of Everest from bottom to top into:

a. Lower Calcareous layer (seen only in the Rongbuk Valley)

b. The Everest pelites

c. The Everest limestones (including the pelitic limestones, the famous yellow band of the northern expeditions).

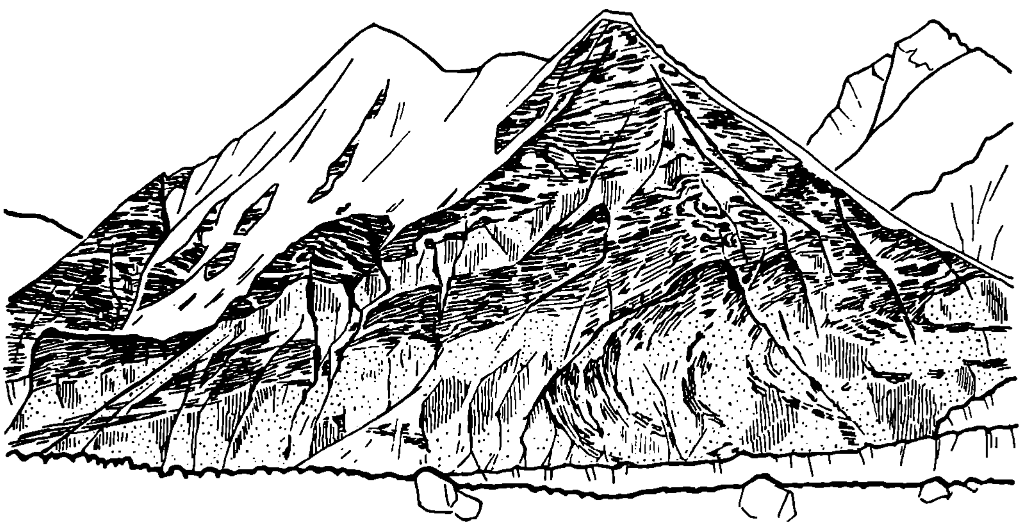


Fig. 108 *Intrusion of Makalu granite into already existing south-vergent gneiss folds* in east shoulder of Cho Polu, Upper Barun Glacier. Everest region (on right background Lhotse); lines = gneiss, dots = granite; reproduced after P. BORDET (1961)

The lower calcareous layer belongs with the section of dark green gneisses and phyllites, but has so far not been found in the higher peaks, except for a doubtful occurrence referred to by BORDET in the south wall connecting Nuptse Peak with the Lhotse. It was studied at the northern entrance of the Rongbuk Valley and at the snout of the Rongbuk Glacier. Here the Lower limestones, altered to marbles, are cut by granites of the Makalu type, as indicated on WAGER's section (Fig. 109). Curiously enough, the mostly lit-par-lit granitic intrusions are more frequent in the northern Everest sediments than in the southern, topographically higher parts. This may be related to the regionally southwards-decreasing Makalu granite intrusion.

The Everest pelites grade from the basal dark, fine gneisses over phyllites into a 1000-1500 m thick section of dark greenish grey argillaceous sandstones, argillaceous sandy limestones and siltstones. They often have a hornstone-like ap-

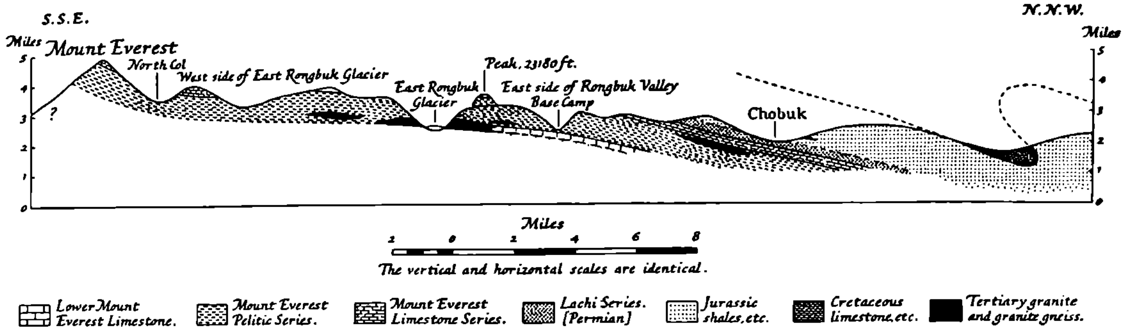


Fig. 109 *Section through Everest and Chobuk,* reproduced after L. R. WAGER in TILMAN (1948)

pearance. GYSIN and LOMBARD (1959, 1960) described samples collected by climbers of the Swiss Himalayan expedition in 1956 from Lhotse and Everest. From the pelitic sections they mention chloritic to sericitic calc-schists, sandy calc-schists, and quartzitic and chloritic hornstones. Predominant among them are fine sandy, sericitic quartzitic to feldspathic calcareous pelites. Biotite porphyroblasts, often chloritized, reach rather high up in the section, and have been collected from 8000 m on the South Col. Chlorite is mainly responsible for the greenish aspect of the pelites. Together with a marked sericitization of the acid plagioclases, it indicates diaphtoresis for the upper pelitic section. As a whole the pelites are well bedded. We have already mentioned the sill-like intercalations of granites, rare in the main peak but more frequent in the lower northern slopes. Actual dykes seem rare in the higher layers, though frequent at the base in connection with the Makalu granite intrusion. Some structural complications are visible in the Everest pelites along the NW spur, plunging into the upper Rongbuk Glacier (Fig. 110).

The Everest limestone forms an erosional relic on the top part of Everest and is completely surrounded by the pelitic formation. It reappears further to the north as a flat north-dipping

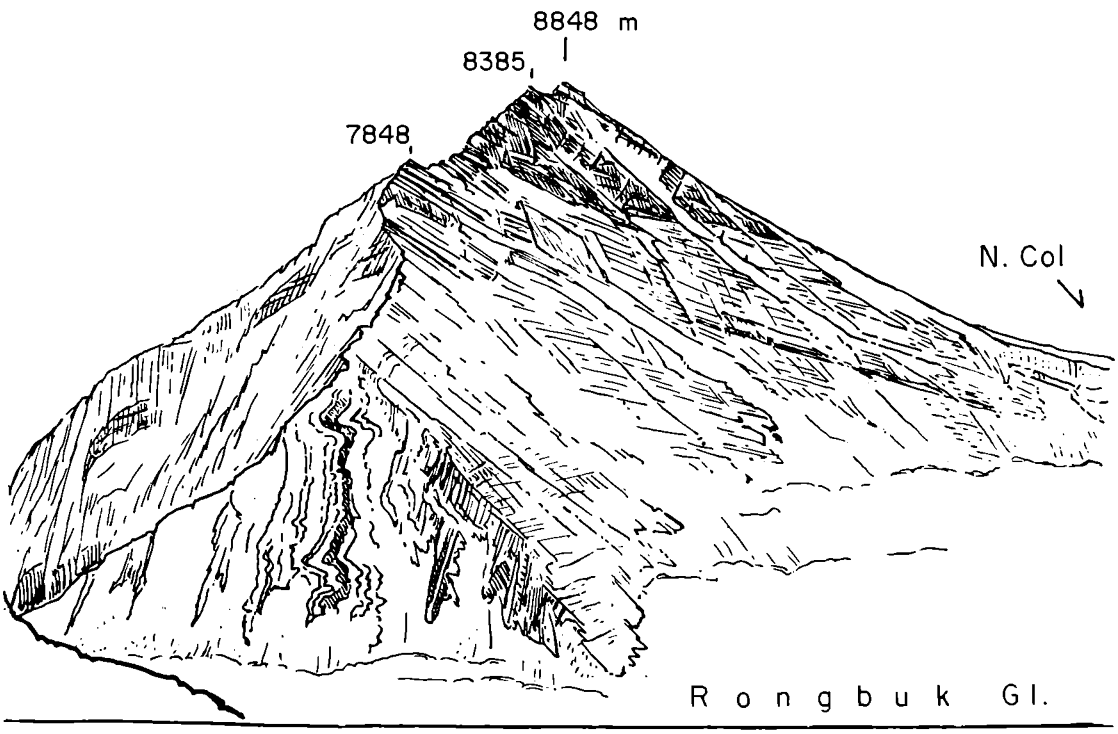


Fig. 110 *Everest seen from Lhapka-La,* with steep folds in pelitic series. Summit topped by Everest limestones. View towards SSW; drawn after photo in TILMAN (1948)

table on the *Changtse Mountain* (Fig. 110, Ph. 42, 43, 44).

The Everest limestone contrasts with the pelites by its lighter colour and particularly by its basal *yellow band*, famous in the history of the northern climbing expeditions. The yellow band consists of schistose limestones and is covered by the greyish, arenaceous, schistose, and more or less dolomitic limestones forming the main rock type. WAGER (1939) gives a detailed description of the Everest limestones. A very fine banding is conspicuous; the bands, only a few millimetres thick, are marked by an alternation of sand grains and more calcareous bands. The sandy detrital parts consist mainly of quartz, fresh feldspar and muscovite, and must have been derived from some granitic material. The calcareous zones include small idiomorphic dolomite crystals. Argillaceous material is missing (Ph. 45).

The author has examined the *limestone samples from the summit of Everest* collected in 1956 by the Swiss expedition and described by GYSIN and LOMBARD (1959, 1960) and also those brought back by the American team in 1963. The latter samples were received through the courtesy of G. O. DYHRENFURTH. The various summit samples are lithologically quite identical. They consist of fine-grained, thin-bedded grey calc-schists or platy limestones. The calcites are elongated conformably to the schistosity, which seems to parallel the bedding. The detrital grains are mostly quartz, acid plagioclases and some microcline, together with fine sericite lamellae, paralleling the calcites.

Of special interest is the fact that both samples contain *crinoidal fragments*. Their large uniform calcite crystals contrast with the otherwise much finer crystalline matrix. In one elongated stem fragment the segmentation is visible (Ph. 46), while one small plate still shows the well-preserved perforation (Ph. 47).

These remnants, representing the *highest fossils of the world* are unfortunately not sufficiently well preserved to allow an age determination of the top Everest limestone. They do, however, support rather than contradict the Carboniferous (to Lower Permian) age generally assigned to the Everest limestones on the grounds that they are overlain by the (Upper) Permian Lachi Series (Fig. 111), (ODELL, 1943; WAGER, 1939).

TIBETAN OR TETHYS HIMALAYAS OF NEPAL (THAKKHOLA REGION)

The oldest sediments of the Main Himalayan thrust sheet have been included in our description of the Higher Nepal Himalayas because they cap Mount Everest. The rocks following stratigraphically above the Everest limestone, already within the southern Tibetan area, will be discussed in the chapter dealing with Sikkim. The only other region still within Nepal where Tethys sediments have been studied is the northern part of western Central Nepal, generally known as the Thakkhola (Mustang) area. The great geological interest of this area has already been stressed, and through the investigations of several geological expeditions it has become the best known part of the Nepal Himalayas.

The Thakkhola region follows north of the high range crowned by Daulagiri and Annapurna, and is traversed by the upper Kali Gandaki River. The northern part of this region, particularly towards the Tibetan border, already has the character of the dry Tibetan highland, with large gravel terraces masking some of the otherwise well-exposed geology. It is to the merit of HAGEN that he recognized the geological importance of this area. The first geological information was obtained from samples collected by the French Annapurna expedition (ICHAC and PRUVOST, 1951). This short account gives a strikingly good picture of the regional geology. Most important was the first recognition of the Spiti section, though Spiti ammonites from Nepal have been exported as ammulets since early days (REED, 1908).

Stratigraphy of the Thakkhola region

The Thakkhola region is generally characterized by fossiliferous sediments, and the latest investigators agree on a general stratigraphy, although only on very regional lines. Evidently every new find of fossils will bring additional data which may, to some extent, invalidate previous assumptions, often arrived at through interpolation of widely spaced facts.

The following description is based mainly on HAGEN (1959 b) and BORDET (1961), but it also incorporates some of the newest information by EGELER, kindly placed at my disposal (manuscript of EGELER et al, 1964), (Fig. 105).[1]

[1] After having completed the present text the writer received, through the courtesy of H. KÜPPER (Director of the Geologische Bundesanstalt, Vienna), a preliminary draft entitled: *Beitrag zur Kenntnis des Paleozoikums der Tibetischen Zone in Dolpo (W-Nepal)* by G. FUCHS, who was attached as geologist to the Austrian Dhaula-Himalaya Expedition of 1963. The writer greatly appreciates the permission to refer to this information. The investigated area lies west of the Thakkhola region and the results bring a most valuable contribution to the geology of the Nepalese Tethys Himalayas. Of particular interest is the Ordovician age assigned to the thick basal calcareous section forming the summits of Dhaulagiri and Annapurna and which is compared with the Garbyang series of Kumaon. The presence of a dated thick Devonian section brings new information for the northern Himalayas in general; the section passes through dolomites, marls and phyllites into sandstones and quartzites, and is covered by highly fossiliferous Carboniferous rocks.

From the preliminary map attached to this paper some information of regional importance has been incorporated into the compilation map (Pl. I).

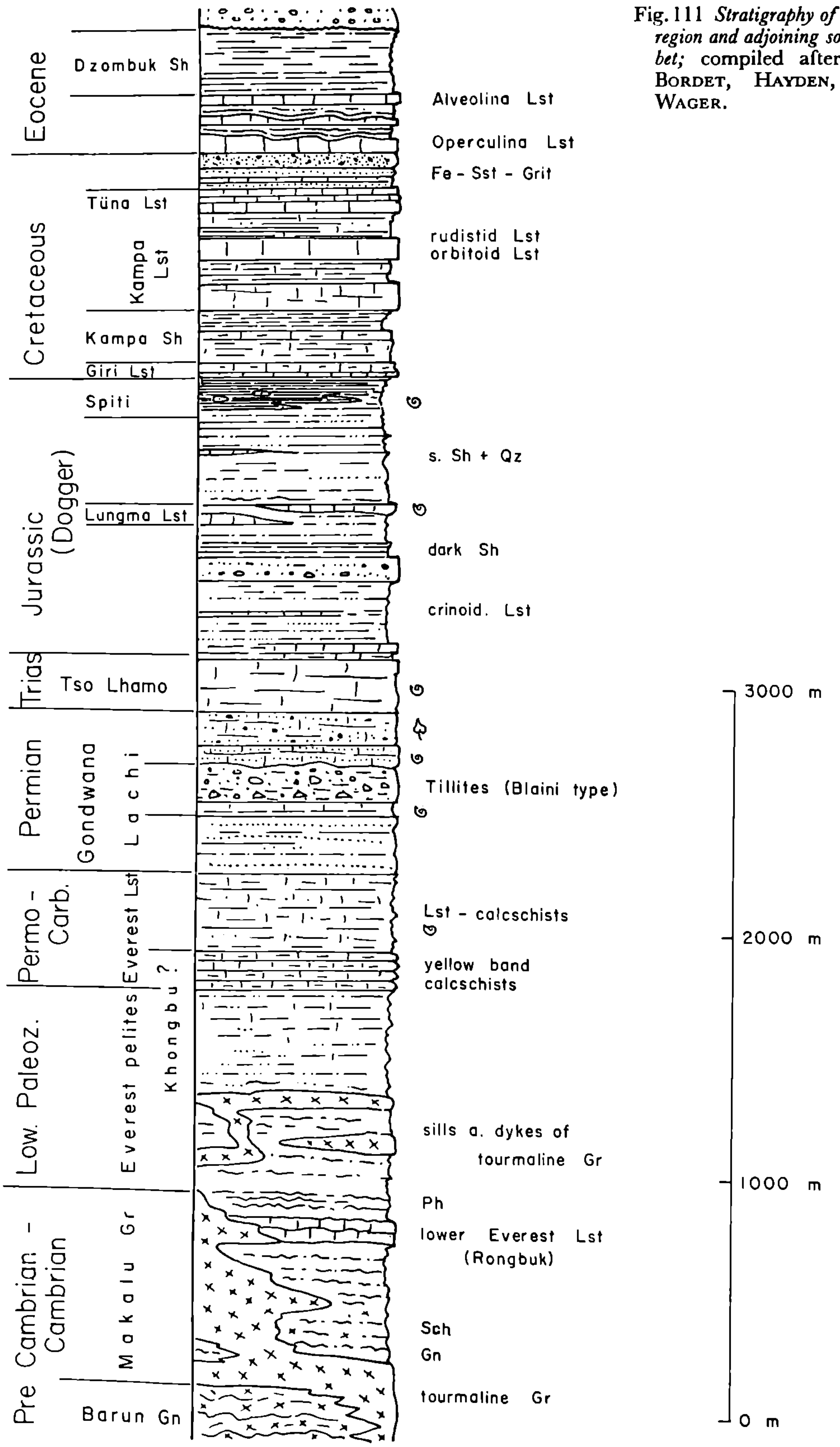


Fig. 111 *Stratigraphy of the Everest region and adjoining southern Tibet;* compiled after AUDEN, BORDET, HAYDEN, ODELL, WAGER.

While discussing the Higher Himalayas, I have already dealt with the calcareous sections, widespread in the Tukucha Basin and reaching into the summit region of Daulagiri and Nilgiri. The *Nilgiri limestones* form a northwards-vergent anticline with a reversed north limb. HAGEN reports biotite-porphyroblast schists and biotite gneisses from the core of this anticline, and EGELER observed gneiss boulders in a western tributary of the Kali River near Tukucha.

The Nilgiri limestones are overlain by arkoses and calcareous quartzites, which are again followed by dark grey limestones and dolomites. In a conspicuous dark shale band EGELER discovered *Lower Silurian* graptolites. This important find shows that all underlying formations are pre-Silurian, and that their Devonian age, assigned by HAGEN and BORDET, has to be revised. With several detrital sandstones and dark shale horizons at their base, the section continues with brownish fossiliferous limestones rich in brachiopods, corals and bryozoans, in which *Fenestella* was noted (EGELER). This section seems to be without trace of metamorphism, while the previous formations all showed a more or less pronounced lower-grade alteration. EGELER believes that this change may correspond to an Upper Palaeozoic (Carboniferous) unconformity. It may, in my opinion, show the last influence of the Gondwana facies. BORDET and EGELER seem to agree in assigning the still higher limestones and lumachelle horizons outcropping at Jomosom to the Triassic. Ferruginous belemnite horizons, partly oolitic, and lumachelle beds represent the *Lower and Middle Jurassic*.

A peculiar horizon, not known elsewhere, is reported by BORDET above the ferruginous zone. He mentions schistose sandstones with plant remains, lignites and silicified wood associated with ferruginous conglomerates containing volcanic pebbles, iron oxide and silex. They are followed by fossiliferous glauconitic sandstones leading into the Spiti shales. As mentioned previously a plant-bearing detrital Jurassic formation was also discovered by the author along the Mangshang River in southern Tibet north of the Kumaon Himalayas (Fig. 86). Its connection with Middle Jurassic belemnite limestones recalls part of the section mentioned by BORDET. In both localities the detrital Jurassic leads into the overlying famous Spiti beds. A comparison with the Angara flora might be of regional interest. We may recall here that up to 3000 m of detrital plant and coal-bearing Lower Jurassic formations are known from the Afghan and Iranian ranges.

The overlying *Spiti shales* have furnished the characteristic ammonite fauna known from the famous type locality. At present we lack the carefully sampled horizons needed for a subdivision of the Spiti section in the Thakkhola region. Such studies would be most important for the fixing of the Jurassic-Cretaceous boundary. Ammonites collected by HAGEN have been recently investigated by RYF (1962). It seems likely that here too the Upper Spiti fauna straddles the Jurassic-Cretaceous border, but the respective palaeontological results must first be controlled in the field on accurately sampled sections. HAGEN has proposed for the Thakkhola Spiti beds the name of *Saligram formation* (the local name for the ammonites used as ammulets). The natural gas which burns as a holy flame in the temple of Muktinath issues from this Saligram formation.

The black concretionary Saligram formation is normally overlain by fossiliferous glauconitic sandstones and siltstones which represent the highest pre-Pleistocene formation in the Thakkhola region. For these EGELER mentions a minimum thickness of 140 m. HAGEN's lithological descriptions are somewhat confused (1959). He mentions fossils of Palaeocene and Eocene age in connection with his Saligram formation 2 km southwest of Tangbe, although EGELER considers his detrital Tangbe formation as an equivalent of the *Giumal sandstones*—a correlation which seems well founded. HAGEN stresses the transgressive and unconformable basal contact of his Saligram formation. In the northwestern Thakkhola, at Thakmar, he describes the Saligram beds as transgressing on Triassic dolomites with a basal breccia, while further to the west, where the beds increase to 1000 m and grade into Flysch-type sediments, they overlap Palaeozoic horizons. These important statements need further confirmation, since corresponding facts are unknown elsewhere in the Himalayas. The transgressive character is contested by the newest investigations of EGELER, who places more weight on the normal conformable position of the Spiti Shales in the Jurassic section.

Of special interest are the *Cretaceous sediments* of the Thakkhola region. From the available information is it not yet clear whether Flysch-type sediments are present, and whether any indication of the exotic Tibetan formations with their ophiolitic vulcanism has been noted. In this connection EGELER's observation of volcanics, including spilitic detritus in the Jurassic and Cretaceous sediments is of great interest. Also the somewhat peculiar ferruginous volcanic pebble layer in the Middle Jurassic mentioned by BORDET deserves special attention. It is hoped that the final studies of EGELER and the present investigations of BORDET will add more facts to this still-puzzling problem. Judging from the regional geological picture, it seems still possible that the eugeosynclinal belt of the northernmost Himalayas may extend somewhere to the north of the Thakkhola region. The wide extension

of impressive, probably Pleistocene, gravel terraces in the northern Thakkhola region emphasised by HAGEN, unfortunately masks most of the underlying sediments. These well-developed terraces could be correlated with the type observed in the upper Sutlej Basin and around Gurla Mandhata. Their composition and morphology are strikingly similar. This is well visible in HAGEN's excellent photograph in his volume on Nepal (1960).

A further complication in this northernmost part of the Thakkhola region is the intrusion of young, most probably late Tertiary, granites. They were discovered by HAGEN and called by him *Mustang granite* (1954). The granite is widespread west of Mustang and forms the higher mountains of this region. HAGEN (1954) mentions a tourmaline granite, which is absolutely massive, but gets gneissose towards the south and seems to grade into *root zone* granites of the Kathmandu nappes. For this reason HAGEN suggests an early to pre-orogenic age for the Mustang and allied granites. BORDET (1961) compares the Mustang granite with the Makalu granite. He also stresses the similarity of the andalusite-bearing tourmaline pegmatites which he collected in the Kali Gandaki River. EGELER (1964) describes the Mustang granite as albite-tourmaline granite, with thermal metamorphism in the country rock. Following BORDET, he believes that the Mustang granite was emplaced *subsequent to the folding of the sedimentary sequence.* He does not deny, however, certain cataclastic movements which are post-granitic. A *post-orogenic age* for the Mustang granite would be in line with the characteristic young tourmaline granites occuring elsewhere in the Himalayas (Badrinath, Makalu, Sikkim and north Bhutan).

Structure of the Thakkhola area

We have already noted that the sediments of the Thakkhola region follow normally above the main crystalline thrust sheet. While the latter still shows a regional northerly dip, conformable to the major thrust sheets all along the base of the Higher Himalayas, the sediments further northwards are thrown into complicated folds, some of them clearly north vergent, with axial planes dipping to the south. Characteristic for the Thakkhola region is, however, a most pronounced N-S-directed *fault zone.* The major fault borders the Thakkhola Valley on its western side. This fault system was first observed by HAGEN, who called the more important western fault the *Dangarjong fault zone.* He considers the Thakkhola region to represent a N-S-directed graben, but admits that the eastern graben border is not clearly outlined (HAGEN, 1959b). In spite of the morphologically sharply delineated Dangarjong fault, HAGEN believes that faulting began in the Rhaetic and thinks that the fault zone is transgressed by the Upper Cretaceous. The fault zone as well as the folding phases north of the main crystalline thrust are thus called early pre-orogenic. This idea is somewhat difficult to follow. According to EGELER, the fault zone, which has a maximal vertical throw of over 2700 m, cuts sharply all existing structures and is clearly regarded as *post-orogenic.*

For the *western and eastern continuation of the Thakkhola sedimentary basin* we must rely entirely on HAGEN (refer footnote p. 166). Westwards the sediments extend for over 100 km into the Langu River basin. They are followed in the south by the basal crystalline thrust and along their northern border by the western continuation of the young Mustang granites. Eastwards they continue for about 50 km, to beyond Manangbhot, until the basin closes. This eastern limit is again formed by a southeastern continuation of the Mustang-type granites. The latter continue into the Manaslu Peak (8125 m)—the famous mountain of the Japanese expeditions. North of Manaslu follows a new and widespread sedimentary zone, the south border of the main Tibetan sediments, which extend uninterruptedly eastwards to the north of Everest. These sediments are clearly visible on HAGEN's photograph (Fig. 3) in his 1954 paper, where he shows a pre-Carboniferous limestone ridge and very well bedded ridges of Jurassic and Cretaceous beds. Unfortunately this sedimentary belt is not discussed in more detail. The steep contact of this sedimentary belt with the granite is well exposed on the summit of Manaslu, visible in the summit picture taken by the Japanese expedition in 1956 (Ph. 48). The banded granite seems to be pegmatitic along the contact, and rich in basic xenoliths which occur swarm-like in the granite. Unfortunately the scientific results of the Japanese expedition could not be consulted by the writer.

Phot. 41 *The Lingtrentse (6701 m)* (1) *and Khumbutse (6617 m)* (2) *seen from the SE spur of Pumori.* Lower contact zone of Makalu granite with injection zone, surmounted by massive granite (Summit of Lingtrentse). On Khumbutse one notes a local fold in the upper contact zone of the granite (phot. N. Dyhrenfuth; copyright Swiss Found. Alp. Res.)

Phot. 42 *South face of Everest* seen from South Col, with south summit (main summit in fog). Note marked bedding and fracturing in pelite series capped by thicker bedded calc-schists (summit). (phot. D. Reist; copyright Swiss Found. Alp. Res.)

Phot. 43 *The south west face of Everest* seen from above Lhotse ridge. View to NNE. Note constant N dip of Everest sediments, pelites in lower part, carbonate rocks in the summit. Approximate contact zone indicated with c. To the left north dipping Everest sediments E of Changtse Tibet, (phot. Indian Air Force; copyright Swiss Found. Alp. Res.)

Phot. 44 *Changtse (7547 m)* seen from main summit of Everest. View northwards. The contact of Everest limestones with Everest pelites is well visible along a sharp line. Dip to north. Western and eastern Rongbuk Glacier join into the main Rongbuk Valley (phot. D. Reist; copyright Swiss Found. Alp. Res.)

Phot. 45 *Typical aspect of well-bedded Everest sediments.* On the south ridge, with Sherpa sipping oxygen (phot. R. Lambert; copyright Swiss Found. Alp. Res.)

Phot. 46 *Stem fragment of crinoid in fine-grained limestones from summit of Everest.* Enl. 40 ×

Phot. 47 *Crinoid plate with well preserved perforations from summit of Everest.* The crinoid fragments is formed by large single calcite crystal contrasting with the fine-grained calcites of the groundmass. Enl. 90 ×

Phot. 48 *The summit of Manaslu* (8125 m) with view towards ESE (the Himalchuli peaks appear to the right). Contact of the northern sedimentary sequence with granites of the Mustang type. Note a pegmatitic layer along the contact and swarms of basic xenoliths in the granite (phot. T. Imanishi)

Phot. 49 *Well bedded quartzites within the Dalings,* locally folded. South of Darjeeling. Prof. Heim gives scale. The fold axes are directed to the NE (phot. A. Gansser)

Phot. 50 *Net-like skeletal garnet in quartzites* of the Daling schists indicating incipient metamorphism. E of Darjeeling. Enl. 60 ×

Phot. 51 *Subfolded Darjeeling gneiss,* Murti River, Darjeeling area. gn = banded gneiss, ps = psammite gneiss, ap = aplitic veins (phot. A. Heim)

Phot. 52 *Tourmaline-pegmatite cutting Darjeeling gneisses* Ghum, Darjeeling area. gn = gneiss xenoliths in pegmatite, t = radially arranged tourmaline in pegmatite, ca = lime silicate lense (phot. A. Heim)

Phot. 53 *Typical lime-silicate lense* (ca) with folded tail end. Darjeeling gneiss, Murti River, Darjeeling area (phot. A. Heim)

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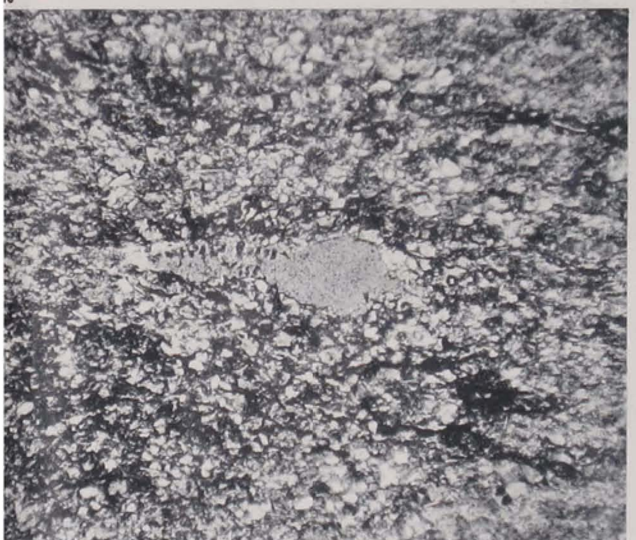

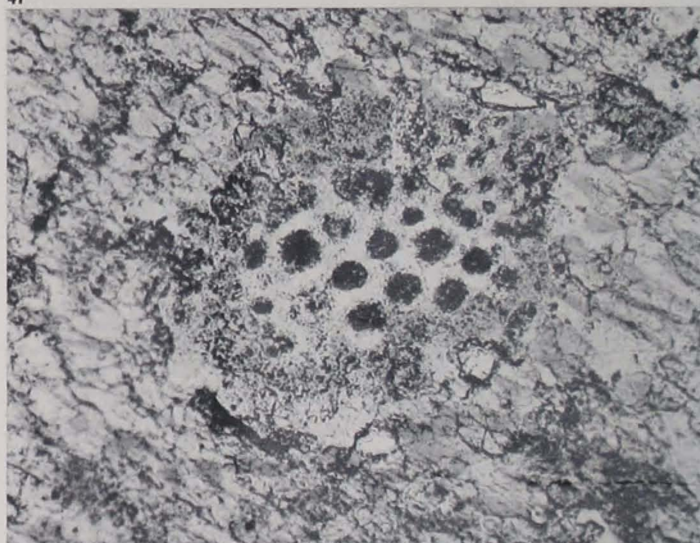

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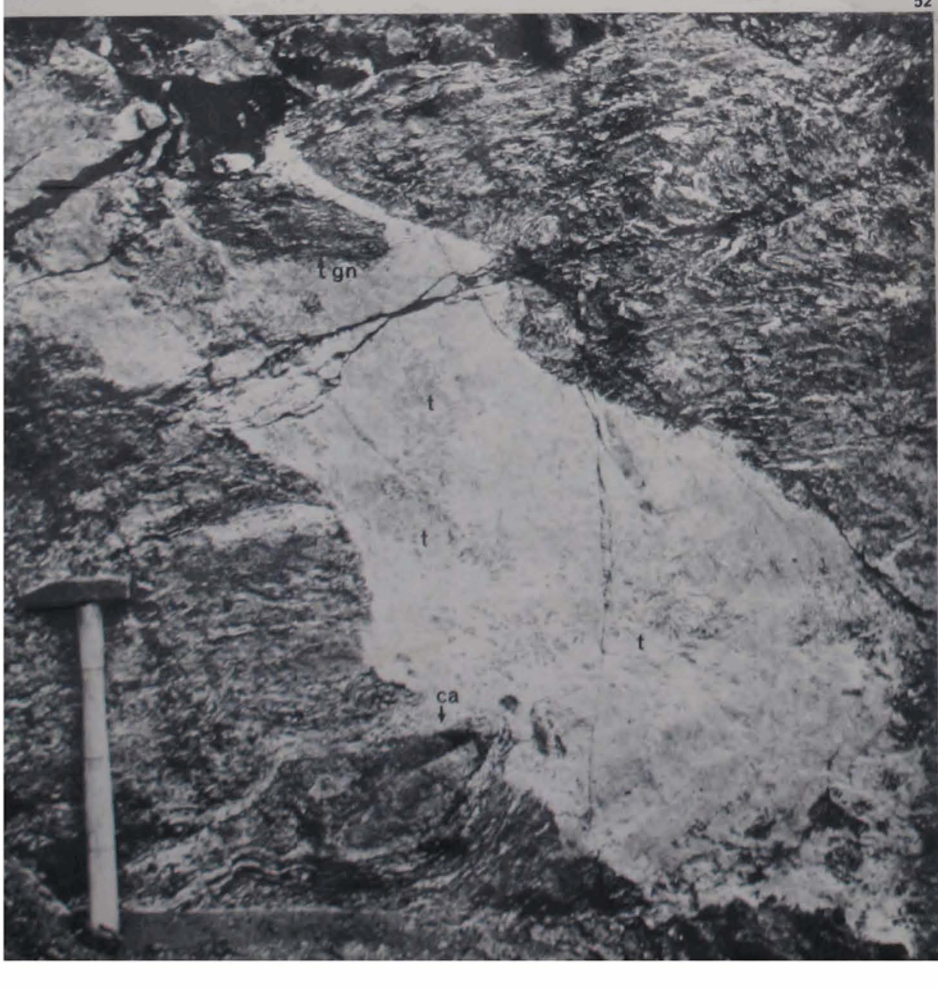

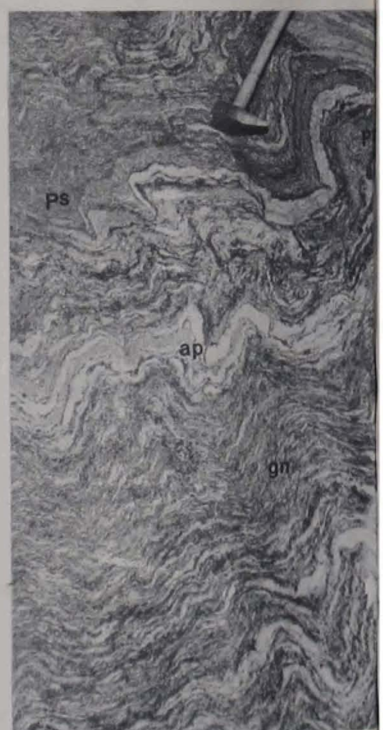

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CHAPTER VIII

SIKKIM-BHUTAN HIMALAYAS

The more one moves eastwards along the Himalayan chain, the more difficult it becomes to undertake geological investigations. Compared to the western ranges, the monsoon seasons in the eastern Himalayas are more severe and frequent wet spells are experienced also in the so-called dry seasons. Rainfall brings an increase of vegetation, and the dense jungles of the eastern Himalayas, reaching the 4000 m level, succeeded by low *Rhododendron* growth, mask a great deal of the geological features. Except for Sikkim, which has always been a transit country for expeditions to Tibet and Everest, the rest of the eastern Himalayas was practically closed to geological investigations and only very few geologists have ever visited these areas. Most of the visits have been restricted to the very foothills, partly in search of coal.

Geological investigations in Sikkim and the adjoining Bengal region began in the middle of the last century. HOOKER, in his famous Himalayan Journals (1854) reports the geological results of his extensive two years travels in many parts of Sikkim. He was able to trace the regional domal picture of the gneisses and observed the overlying bedded sedimentary rocks. He noted crinoidal limestones at Tso Lhamo, the famous lake near the Tibetan watershed. The Darjeeling district and its foothills were examined by MALLET, who has given an excellent account (1875). Following BOSE, who compiled the mineral resources of Sikkim (1891) we find GARWOOD's descriptions, accompanied by the first general map (1903). Northeastern Sikkim is included in HAYDEN's traverse to Lhasa (1907), and VON LOCZY published a geological section from Darjeeling to Kangchendzönga (1907) which he observed as long ago as 1878. Later followed some newer surveys in connection with climbing expeditions, such as DYHRENFURTH (1931) in northwest Sikkim and WAGER (1934, 1939) in northern Sikkim and adjoining southern Tibet while travelling to and from Everest. AUDEN (1935) discusses the problems of the Dalings and Darjeeling gneisses and the geology of the Tso Lhamo region on the Tibetan border. In 1936, the author, with A. HEIM, visited the Tista region, Darjeeling, and made a traverse to Gantok (HEIM and GANSSER, 1939). New mapping by the Geological Survey of India has been carried out in the Darjeeling district in the last 15 years, but no comprehensive report or maps have so far been published (RAY, 1947, Survey Report, 1962).

In Bhutan, some of the foothills have been investigated cursorily by GODWIN AUSTEN (1868), MALLET (1875), PILGRIM (1906) and LAHIRI (1941). Otherwise no geological information has been published, except a few remarks by HAYDEN (1907) on Chomolhari in the northwestern Tibetan frontier region.

The eastern Himalayas have recently become of strategic interest. This has sponsored geological investigations for economic purposes, especially in the Bhutan foothills, where the Geological Survey of India has begun detailed and regional work in the last few years. Of these investigations nothing has been published so far, and it is hoped that some results of these completely new surveys will be available for the International Geological Congress in Delhi in December 1964.

The author, accompanied by his young assistent RUDOLF HÄNNY, made several geological traverses in western and central Bhutan during the spring of 1963. With the permission and most generous assistance of the Government of Bhutan much new scientific information has been obtained, of which a preliminary account will be given in the following. Unfortunately, for various reasons the shipment of our rock specimens was delayed in India for several months, so that laboratory investigations have only begun and the results could not be included in the present account.

The northeastern part of Bhutan and all the inner and northern parts of the NEFA provinces are still geologically unknown and will be discussed in a later section.

For the Sikkim-Bhutan Himalayas we shall adopt the same subdivisions as in the previously

described Himalayan sections, but the remarkable cross structures of Sikkim and Bhutan and the newly discovered sedimentary syncline in northwestern Bhutan hamper in a way a clear division into Lower and Higher Himalayas. Included in the discussion of the Tibetan or Tethys Himalayas will be some remarks on HAYDEN's exploration between northern Sikkim and Lhasa.

SIKKIM-BHUTAN SUB-HIMALAYAS

As in Nepal, the Sikkim-Bhutan Sub-Himalayas are entirely constituted of Siwalik and younger deposits. Extending from Nepal, the Siwalik hills can be followed as far as 20 km east of the Tista River, where they are missing for somewhat over 10 km, then set in again and disappear below the advanced spur of the Lower Himalayas of western Bhutan at the Jaldhaka River. They reappear once again east of the Torsa River in the Baxa Hills (MALLET 1875, PILGRIM, 1906). The continuation further eastwards is not yet well known, except for the observations by PILGRIM in the eastern Bhutan foothills. Apart from the deep erosional gap at Hatisara, observed by the author, the morphological aspect of the foothills suggests a rather continuous trend along eastern Bhutan. Compared to Nepal, the Siwalik foothills of Sikkim and Bhutan are more narrow and, as we have seen, often interrupted.

Good Siwaliks exposures are met along the Tista River (Fig. 112). The deepest outcrops forming the southern margin of the Siwalik Hills consists of bluish grey nodular marls and clays with micaceous fine-grained sandstones. Upwards they grade into a section of 1700 m of grey sandstones dipping northwards at about 45°, still with some marly intercalations in the upper part. In the last 300 m we find sandstones with conglomerate layers, where quartzite pebbles predominate. Northwards, along a tectonic contact, follows a steep layer of tectonized sandstones with dark shales and coal seams. Still further north we meet outcrops of Gondwana-type coal-bearing sandstones with a basic sill, but the Main Boundary Fault is not exposed. This over 2000 m thick clastic section forms the north flank of a normal anticline, the core of which is just exposed at its southernmost outcrop. The thick north flank seems stratigraphically normal, except for the tectonically wedged-in layer of carbonaceous sandstones to the north, already involved in the Boundary Fault. The exposed section could be placed into the Middle to Upper Siwaliks. Curiously enough, the typical brownish reddish clays were not observed.

MALLET (1875) investigated the Siwaliks west and east of the Tista River and again in western Bhutan from a few kilometres east of the Torsa River to the east of the Sankosh River. The average thickness amounts here to 3000 m, a large percentage of which consists of rather soft, massive to thick-bedded, highly feldspathic and micaceous sandstones. They often show the characteristic pepper and salt appearence. Locally calcareous cement forms irregular concretions or is concentrated in thin layers of calcareous shales. Clays and marls are rather rare. Gray shales often contain carbonaceous matter, locally enriched into a soft, flaky coal not unlike the older Gondwana coal horizons. Upwards, pebbles appear in the sandstones, first as a few stringers of white quartz, higher up as true sandy conglomerate horizons. The size of the pebbles rarely exceeds fist size. Quartzites predominate, together with some gneisses and schists. Most of the observed sections seem to be normal, with a rather regular dip of 30-50° to the north or NNW.

East of the Torsa River, along the western Bhutan foothills, the Siwaliks form outcrops dipping up to 70° to the NNE. At their base MALLET mentions dark reddish, soft, earthy sandstones with red mottled clays. Above these follow the typical massive pepper and salt sandstones with upwards-increasing conglomerates. The latter seem to occur more frequently in this area than in the foothills along the Tista River.

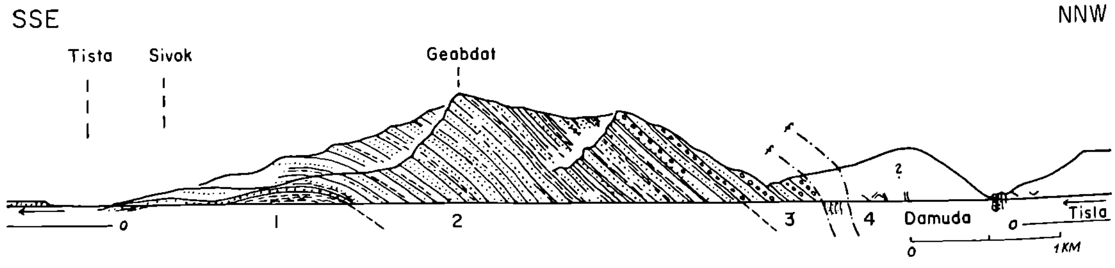


Fig. 112 *Siwalik hills along Tista river.* Sikkim Sub Himalayas; after HEIM and GANSSER (1939)

1 bluish clays and marls
2 grey sandstone with thin marly zones
3 sandy conglomerates
4 scattered Damuda outcrops

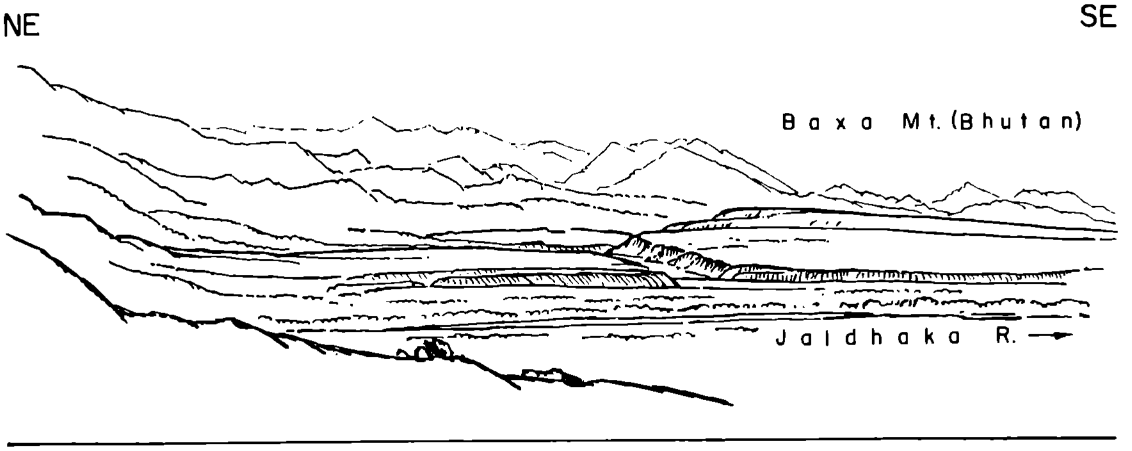


Fig. 113 *The warped terraces in the Jaldhaka River area,* Border zone Sikkim-Bhutan Sub-Himalayas; after Heim and Gansser (1939)

The lower reddish section is directly comparable with the Nahans. They seem to be less widespread than in the western Himalayas, and are often missing altogether, being replaced by bluish grey pelitic beds.

Pilgrim describes a very similar Siwalik section from the foothills of eastern Bhutan. The regular 50-60° north-dipping Siwaliks begin at the base with bluish clays and fine argillaceous sandstones, overlain by coarser micaceous pepper-and-salt-type sandstones, followed by pebbly sandstones and conglomerates near the over 60° steep Boundary Thrust. The sandstones contain lignitic wood remains. Quartzites predominate as pebbles in the conglomerates, while gneisses are missing. The 3000 m thick section seems to range from the Middle towards the Upper Siwaliks, without a marked boundary. The characteristic reddish brown pelites seem absent, and bluish colours dominate. The question arises whether environmental conditions were different in this part of the Himalayas; an increased humidity, stronger erosion and less lateritic weathering are possible explanations. A climatic difference does exist at present, and similar conditions may have been likely during the Middle to Upper Siwalik deposition.

Apart from the Siwaliks, the Sikkim-Bhutan Sub-Himalayas are noteworthy for the abundance of *Sub-Recent and Recent river terraces,* which clearly display the last tectonic displacements. It is of particular interest that some of the best developed terrace systems coincide with the pronounced gap in Siwalik deposits along the Sikkim-Bhutan border region. This fact was already observed by Mallet (1875). He states: "The deposits, which occur all along the base of the hills, may not in reality perhaps be more largely developed here than elsewhere, but they are cut through much more deeply by the rivers; and it is to be noted that this feature occurs in a portion of the strip where the Sub-Himalayan hills and rocks are absent."

Strong erosion and warping of these young deposits is well displayed along the Jaldhaka River, east of the Tista, where the Siwalik outcrop is rather suddenly replaced by large Recent river deposits. In 1936 the author observed a pronounced warping of the three principal terraces forming a hill zone paralleling the mountain front, not unlike an incipient Recent anticlinal structure (Fig. 113, 114). Along the mountain front, the terraces steepen from 5° to over 10°, the older and higher ones showing the greatest inclinations. The higher terraces display some very large boulders of mica schists and gneisses, some of 10 to even 100 cubic metres. The discrepancy of the boulder sizes in the recent alluvial

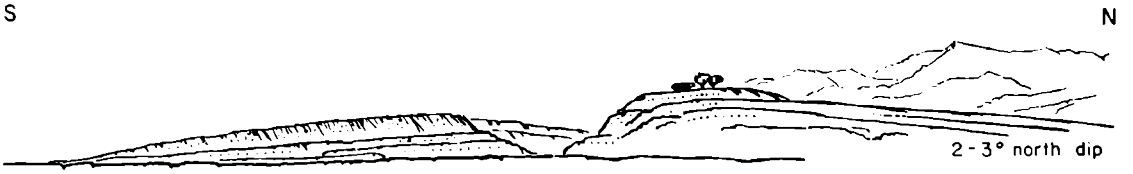


Fig. 114 *The folded terraces near Jaldhaka River,* forming an incipient anticline, paralleling the foothills. Sikkim-Bhutan Sub-Himalayas; after Heim and Gansser (1939)

deposits compared to the relatively small pebbles of the Upper Siwaliks is striking and supports the conception of a very pronounced young morphogenic uplift of the Himalayas.

SIKKIM-BHUTAN LOWER, HIGHER AND TIBETAN HIMALAYAS

Our newest regional investigations in Bhutan have shown that the Lower as well as the Higher Himalayas of Bhutan differ considerably in their geological aspect from the Himalayas of Sikkim. Sikkim, which covers a smaller section of the mountains than Bhutan is more simply built and it seems therefore preferable to discuss the two areas seperately as far as the Lower, Higher and Tibetan Himalayas are concerned. HAYDEN's investigation in southern Tibet will be discussed under the section dealing with Sikkim.

THE SIKKIM LOWER HIMALAYAS

The regional geological outline of Sikkim's Lower Himalayas is rather simple, as far as is known from the available surveys. We recognize a domal cross feature, with a core of uniform Daling slates and schists overlain by gradually increasing metamorphic horizons, ending in widespread gneiss sheets wich support the highest mountains to the west and north. On the southern front, a narrow strip of Gondwana rocks is wedged between the Siwaliks and the older Dalings. Patches of Gondwana sandstones were recently reported from further inland, within the Daling area (GHOSH, 1952 and General Reports, 1962) which indicates that the regional picture is not after all as simple as hitherto visualized (see below).

All along the foothills of the Darjeeling district, south of Sikkim, the Siwaliks are steeply overthrust by formations belonging to the Damudas (Lower Gondwanas). The thrust zone is generally badly exposed, but judging from unconnected outcrops along the Tista River, the thrust planes are dipping at 60-70° towards the north. This thrust zone coincides with the well-known Main Boundary Fault, which extends for the whole distance along the Himalayan range.

Gondwanas (Damudas)

The Damudas are characteristic coal-bearing detrital rocks, their fossil flora indicating a Lower Gondwana age. Detailed sections are known from MALLET's survey for coal (MALLET, 1875).

The predominant rocks are feldspathic, partly micaceous brownish sandstones, shaly micaceous sandstones often with plant impressions (*Glossopteris*), carbonaceous shales, and coal seams. Up to 12 coal seams are met, suggesting a kind of cyclic sedimentation. It has been suggested that most of the sections are inverted, dipping steeply towards the north. This is supported by the fact that frequently sandstones top the coal seams, while carbonaceous shales lie below them. Generally the coal is highly sheared and frequently altered to anthracite, with reduced volatile elements, and some of the carbonaceous shales become graphitic and the sandstones often quartzitic. The best coal seams measure about 3 m (Tindharia region) with sandstone on top and shales below. In the same region Fox has found a boulder bed which may be glacial and could be correlated with the Talchirs (Blainis). Nearby he observed the characteristic mica peridotites which are typical for several Gondwana coal fields of Peninsular India (Raniganj) (Fox, 1934).

Because of the highly tectonized aspect of the Darjeeling Damudas, it is difficult to compare these sections with the well-known Damudas of Peninsular India. The presence of boulder beds suggests Lower Damudas or the Barakar formation, while the flora and lithology of the coal-bearing layers rather point to the Upper Damudas or the Raniganj formation of the shield area (Fox, 1934). It appears that the Himalayan Damudas are a tectonized relic, with both sections highly reduced. The total thickness of the eastern Himalayan Damudas does not seem to exceed 1000 m.

Northwards, the band of Damudas is succeeded by the very uniform and characteristic Dalings of the Sikkim area. They border the Damudas with a very sharp thrust contact, dipping steeply towards the north. No change in strike or dip is visible on either side of the contact, which is very well marked by the different lithology. The Baxa formations with their limestones, dolomites, variegated slates and quartzites are missing; they first come in at the western border of Bhutan and are well displayed in the Baxa Hills. 30 km north of the Daling thrust, in the Rangit Valley north of Darjeeling, GHOSH (1952) described Damuda outcrops covering an area of over 100 sq. km. The rocks exposed are feldspathic sandstones and carbonaceous shales carrying a semi-anthracitic coal. At the base of the section there are tillites and varved slates with embedded pebbles and boulders of quartzites, limestones, phyllites, cherts, granites and gneisses. The coal measures are cut by dykes of serpentinized "mica-lamprophyres". Of special interest was the find of *Spirifer* and other Permo-Carboniferous fossils in the pebble beds north of Namchi. The fauna resembles that found by WAGER in the Lachi Series (WAGER, 1939).

The Damudas of the Rangit Valley are invariably overlain by Dalings, the contact dipping

northwest on the west side of the Rangit River and northeast or east on the eastern side. The dips vary from 15-80° and local tectonic complications are frequent. The Damudas seem to occur in a *tectonic window*, cut into a north-south-directed cross fold in the overlying Dalings and Darjeeling gneisses. It is interesting to note that as early as 1903 GARWOOD mentions carbonaceous shales and quartzites from the same localities.

southern border, the quartzitic slates display a regional north dip, but are complicated by minor disturbances, which indicate a clearly south-vergent tectonic style with north-east-directed fold axes ("b" type), (Fig. 115 and Ph. 49). However, further inland the generally rather gently undulating Dalings locally expose steep disturbed zones resembling cross folds, the significance of which is not yet understood. The reported Da-

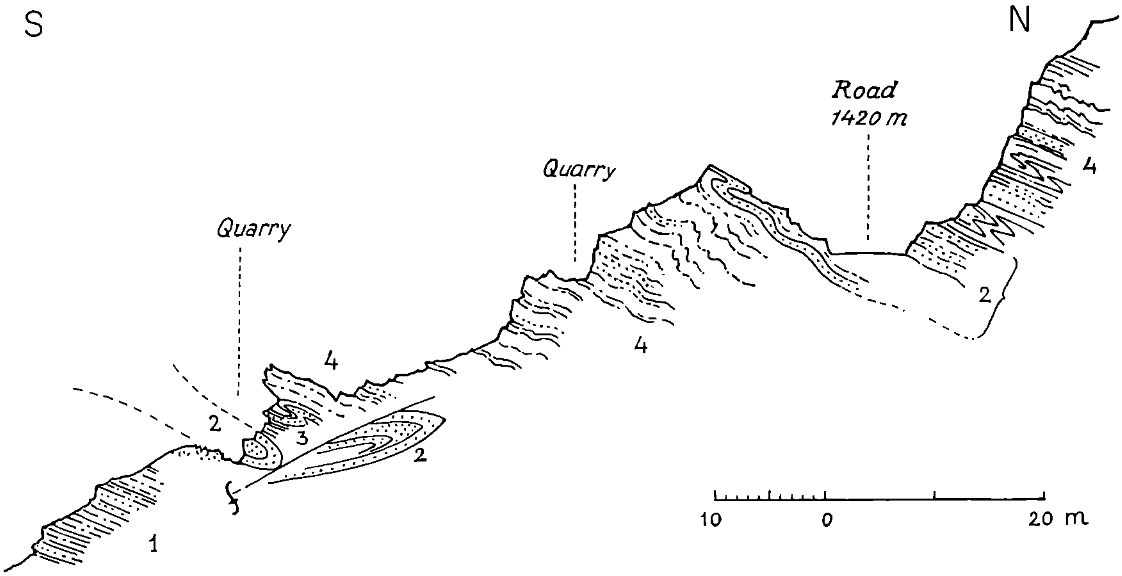


Fig. 115 *Small south-vergent folds in the metamorphic quartzitic Dalings south of Darjeeling.* Lower Sikkim Himalayas after HEIM and GANSSER (1939)

1 mica schists
2 well bedded quartzites
3 psammite gneiss and quartzites
4 garnet schists and quartzites

Dalings

The Dalings, a term coined by MALLET, consist of typically greenish fissile slates varying from greenish greasy-feeling clay slates to more or less green quartzitic schists. Slaty and quartzitic layers often alternate, but the argillaceous type dominates. The Dalings are remarkable for their constant development and the monotonous lithology over a great thickness. They seem to be a characteristic representative of the late Precambrian to early Cambrian argillaceous sequence which we have already met in the more western Lower Himalayas (Simla and Dogra slates), and which may represent a marginal facies of the Vindhyans of the Peninsular shield area.

The Dalings are well developed all along the lower and middle course of the Tista River, and form the over 50 km long core of the large north-south-directed domal uplift dominating the Sikkim area. This regionally simple picture is complicated by local disturbances. Marginally, on its muda remnants, which, judging from the general tectonic picture, occur in window-like outcrops, claim our special attention.

The most impressive geological feature, however, in the Sikkim area, and as we have already noted in many sections of the Lower Himalayas, is *the upwards progressively increasing metamorphism of the Dalings.* We note, climbing from the bottom of the Tista River to the heights of Darjeeling, a very gradual change from clay slates to granite gneisses. Owing to the monotonous and rather constant lithology of the Dalings, the gradual increase in metamorphism is here particularly well displayed, so that the Darjeeling area has become the classical ground for the inverted metamorphism. It is therefore interesting to indulge in somewhat more detail here.

Structural lines and metamorphic isogrades of the Sikkim dome mostly coincide. Along the eastern and western border, the gneisses begin at approximately 1000 m above sea level, while in the central part hills reaching over 3000 m

still consist of Daling slates. The western slope of the dome is somewhat steeper than its eastern side, and here the abnormal north-south strike is more pronounced. Even the gneisses of the eastern side of Kangchendzönga strike north-south.

On most maps, our present one included, the contact of the Daling slates against the gneisses, in spite of being completely transitional, is shown as an abnormal contact. With this symbol we want to show the abnormal inverted metamorphism, and since the competence of the more compact gneisses is different from that of the underlying argillaceous sections, disharmonic disturbances may coincide with this level, suggesting a major displacement even where it does not exist. On the other hand one must realize that in some instances larger thrusts can develop out of such primary minor disturbances. This is seen to the west of the Sikkim uplift, where the gneiss base develops into real thrust sheets, well displayed in Nepal, though many contacts are still transitional, such as those mentioned by AUDEN (1935) in the Arun Gorge and northwest and east of Kathmandu. The argument between advocates of a thrust contact and those who prefer transitional sections remains somewhat futile as long as the actual amount of the displacement is not considered.

The section from the Tista Gorge to Darjeeling is probably the one where disharmonic displacements are minor and where the gradational change is best displayed. We investigated this section in 1936, and some of the facts are put forward in the following paragraphs (HEIM and GANSSER, 1939).

In spite of the gradual changes, a three-fold division has been suggested for the complete section, from bottom to top:

Daling schists
garnetiferous mica schists
Darjeeling gneisses

Daling schists

In the lower Tista, the deepest Daling outcrops consist of greenish clay slates alternating with some greenish sandy quartzites. Upwards we observe chlorite-phyllites, sericite-chlorite schists and sericite-chlorite quartzites. Rutile can be locally enriched in the quartzites. Gradually small biotites occur together with some epidote, leading to sericite-chlorite-biotite-epidote schists. Some of the chlorite has developed from the biotite, indicating local diaphtoritic changes. The chlorite of the bulk of the lowest grade Dalings is, however, not derived from biotite. The biotites are mostly greenish pleochroic porphyroblasts and not detrital flakes, and indicate a gradual change from an epi- to a meso-metamorphic phase. It is not yet ascertained whether the chloritoid zones, observed during the recent investigations of the Darjeeling region by the staff of the Geological Survey, conform to the regional metamorphic zones or whether, as according to BANERJEE "the distribution of chloritoid in certain areas is in complete discordance with the pattern of the regional metamorphism of the area" (General Report, 1962, p. 9).

Garnetiferous mica schists

This next metamorphic group begins with the formation of garnets. In the more quartzitic zones the garnets form net-like grain aggregates (Ph. 50). In the argillaceous horizons muscovite and biotite increase and the garnets are more idiomorphic. With the chlorite, the green colour of the Dalings has disappeared. We distinguish garnetiferous muscovite-biotite quartzites and garnet-muscovite-biotite schists. The biotite is now brown, and differs from the green one of the lower section. Increase in metamorphism is often indicated by kyanite-staurolite-garnet-two-mica schists. They represent the classical *meso grade*, combined with some stress effect. Locally kyanite can be enriched in quartz veins forming up to 10 cm long crystals.

Darjeeling gneisses

Gradually feldspars and layers of quartz appear which give the often intensely subfolded rocks a banded appearance (Ph. 51). Most of the feldspars are acid plagioclases, while orthoclase is generally subordinate. The more quartzitic rocks have been altered to garnetiferous two-mica psammite gneisses, with a predominance of biotite over the muscovite. The plagioclase is mostly albite-oligoclase or oligoclase-andesine. Gradually the muscovite disappears and garnetiferous biotite-psammite gneisses dominate. More argillaceous layers are metamorphosed to sillimanite-biotite gneiss, with or without some garnets. Here orthoclase is represented, together with some albite. The sillimanite can be enriched in layers, changing the granoblastic texture into a fibroblastic one. Locally, sillimanite forms gliding planes with silky shining surfaces. The sillimanite gneisses represent the typical *kata phase*. In extreme cases, the gneisses can become further mobilized, with locally granitized zones, leading to muscovite-biotite-granite gneisses rich in orthoclase and microcline with some albite.

The foregoing has shown that a gradual increase from epi-, over meso- to the kata-metamorphic phase can be observed. Each phase has its typical minerals, which have been formed under the prevailing temperature and stress conditions

without the introduction of foreign agents. This fact seems rather important and has been confirmed by comparative chemical analyses. The results obtained and observed for the argillaceous facies are tabulated as follows:

Metamorphic phase[1]	zone mineral	representative rock types
Epi phase	chlorite-sericite (green biotite)	chlorite phyllite chlorite-sericite schists chlorite-biotite-sericite schists
Meso phase	brown biotite, muscovite staurolite, kyanite, garnets	garnet-biotite-muscovite schists garnet-biotite schists garnet-kyanite-staurolite-two-mica schists
Kata phase	sillimanite	(garnet) sillimanite-biotite gneisses

[1] The old classical subdivision into *Epi, Meso* and *Kata* metamorphic phases is preferred to a division into mineral facies, since insufficient petrographic data exist to allow a workable sequence of facies minerals in the Himalayas.

Chemical composition (after HEIM and GANSSER, 1939):

Daling schists

SiO_2	54.73		
Al_2O_3	22.39		
Fe_2O_3	3.05		
FeO	4.01	*Niggli values*	
MgO	1.61	si	202
MnO	0.02	al	48.5
CaO	0.59	fm	30
Na_2O	1.79	c	2.5
K_2O	5.43	alk	19
TiO_2	0.80	k	0.67
P_2O_5	0.14	mg	0.30
H_2O+	5.42	ti	0.02
H_2O-	0.18		
	100.16		

Sillimanite-biotite gneiss

SiO_2	66.68		
Al_2O_3	16.87		
Fe_2O_3	1.87		
FeO	4.39	*Niggli values*	
MgO	1.85	si	330
MnO	0.08	al	49.5
CaO	0.68	fm	31.5
Na_2O	1.12	c	3.5
K_2O	3.27	alk	15.5
TiO_2	1.00	k	0.66
P_2O_5	0.09	mg	0.20
H_2O+	1.96	ti	0.38
H_2O-	0.18		
	100.04		

Pegmatites and aplites are rather frequent in the Darjeeling gneisses. Some already occur in the garnetiferous mica-schists. Mostly they are muscovite-tourmaline pegmatites with rare biotite (Ph. 52). Basic rocks are developed as sills, and are less frequent than the acid dykes. Some are quartz-actinolite amphibolites, others biotite amphibolites. Quite surprising is the presence of an anorthoclase-bearing biotite amphibolite.

Of special interest are the *lime-silicate inclusions* or concretions in the Darjeeling gneisses. Not observed in the lower grade phases of this area, they seem restricted to the gneisses, and have been observed in similar gneisses in Central Bhutan and elsewhere.

The inclusions usually form lenticular bodies, with curiously bent tail-ends (Ph. 53). Free lime is rarely present, but a concentric arrangement of a characteristic mineral paragenesis can be observed. From the host rock to the core of the concretion we note:

1. Quartz, oligoclase-andesine, biotite, garnet (country rock)
2. Quartz, little andesine, little biotite, garnet, titanite (contact)
3. Bytownite, green hornblende, garnet, quartz, titanite (contact)
4. Bytownite, garnet, diopside, quartz, titanite
5. Bytownite, quartz, fine reticular garnet (titanite).

Introduced quartz commonly surrounds garnets and bytownites. Some other concretions have a core of pure red garnet with grains up to 2 cm. The latter show characteristic sieve and drop-like inclusion of magnetite and quartz often concentrically arranged, similar to garnet-bearing

schists and gneisses in the central thrust of Kumaon. More basic inclusions or concretions have been observed in the form of diopside-bearing garnet hornblendites. They are often more lenticular and can form actual layers.

The regional picture, as outlined above, fits only in a very general way. With intensified investigations, more discrepancies will be noted, as the presence of Damudas within the Dalings area has already shown. Even during the authors investigations in 1936 it was evident that not only gneisses of the Darjeeling type were present. Within the Dalings of the middle Tista Valley we observed a 100 m thick lens of a uniform two-mica-augen gneiss rich in microcline which forms most of the augens. Marginally the gneiss is strongly mylonitized. The biotite is altered to chlorite, the muscovite to sericite. Green phyllonitic layers limit the gneiss body towards the Dalings. The strongly diaphtoritic gneiss seems foreign to the Daling environment, and may represent an older, tectonically emplaced gneiss, unrelated to the Darjeeling type. The presence of abnormal dips in the wider Darjeeling gneisses as well as intercalations of quartzites and schists, recognized by GARWOOD as early as 1903, indicate further complications.

Comparing the observations of this area with those of other areas of the Himalayas, we note that *Darjeeling type gneisses are very widespread*, mostly in regions where inverted metamorphism takes place in argillaceous formations. We shall note similar rocks, for instance in the Lower Himalayas of Bhutan which match the Darjeeling gneisses in every detail.

The interesting problems arising from the geology described above have been recognized and, in part, discussed since the earliest days of exploration in Sikkim. MALLET (1875) noted the gradation from the lower Dalings to the overlying Darjeeling gneisses. He discusses the possibility of inversion, but believes that the superposition of the gneisses is normal and that the gneisses are younger than the Dalings. Having also observed the reversed contact of the Dalings with the underlying Damudas, he concluded that the Dalings are younger than the Damudas. VON LOCZY (1907), during his traverses in 1878 observed the reversed profiles and in 1883, during a lecture at the Hungarian Geological Society, postulated an enormous recumbant nappe-like fold, with the Darjeeling gneiss overlying the younger beds for over 25 km. As mentioned previously, this is probably the first instance of an indiscriminate application of the nappe theory in the Himalayas. SUESS (1885, 1901) discusses the Darjeeling gneisses and regards *nappism* as a solution for many of the Himalayan problems. AUDEN (1935) summarizes the features of the Dalings and Darjeeling gneisses very clearly and discusses the thrust hypothesis of DYHRENFURTH and WAGER as opposed to the theory (ventured by HERON and supported by AUDEN) that granite under regional stress has invaded the upper part of the Dalings, resulting in the Darjeeling gneisses. RAY (1947) has given a detailed description of the Darjeeling area and stresses the zonal metamorphism. The problem of inversion is discussed, without arriving at a final solution. I do not want at this point to discuss the genetic problems arising from the facts so far outlined. Most important is *the age of the metamorphism and its relation to the tectonic phases*. In many instances the former is post-tectonic, or at least late tectonic, and this evidently greatly complicates the already difficult solution.

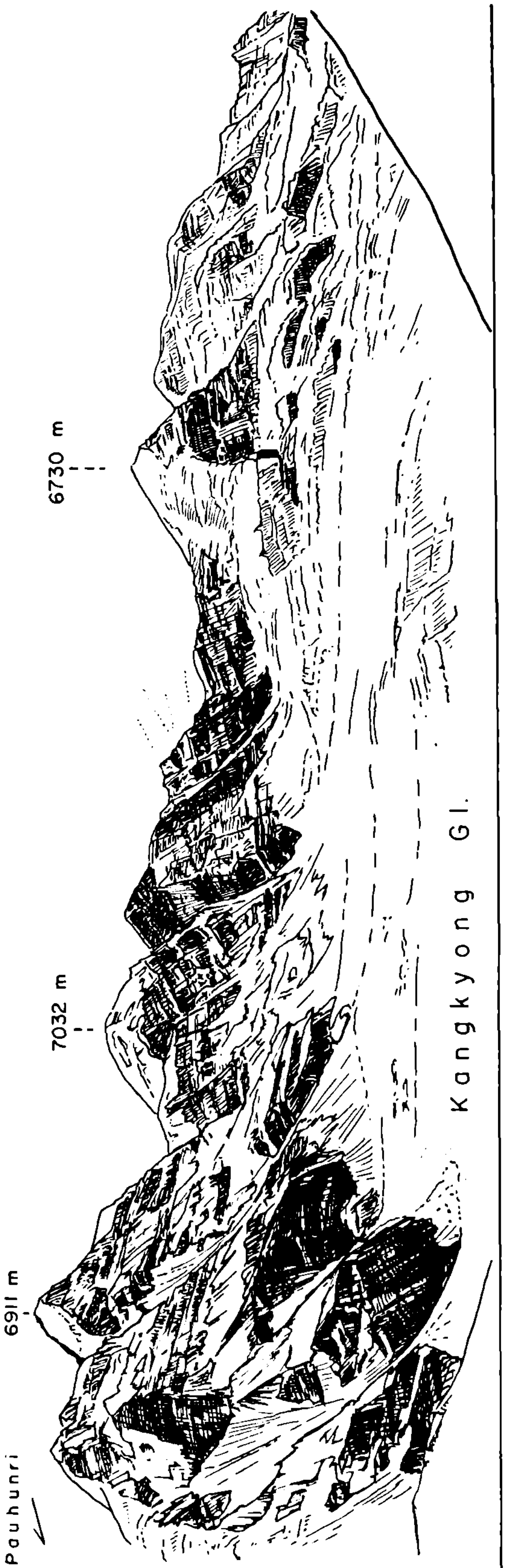
SIKKIM HIGHER HIMALAYAS AND ADJOINING SOUTHERN TIBET

The Darjeeling gneisses surrounding the Tista dome on its west, north and east side, can be followed into the Higher Himalayas of Sikkim. Towards the northwest they form the synclinally situated Kangchendzönga massif. Northwards we find them in the basal part of the Kangchengyao-Pauhunri Range as the base of the Tibetan sediments to the north. Northeastwards the Mesozoic formations of the upper Chumbi Valley south of Phari Dzong, as shown by HAYDEN, complicate the picture, and lead to the geological features of Bhutan to be dealt with in the next section.

All the impressive peaks enclosing Sikkim to the north show regional dips to the north, northeast or northwest (Fig. 116). As far as is known, they are topped or covered on their northern slopes by the sediments of the Tibetan Himalayas. Excepting the 8597 m high Kangchendzönga, these sediments also cap the high peaks.

Kangchendzönga

Kangchendzönga consists entirely of crystalline rocks, in which thick-bedded augen gneisses of granitic origin dominate. They alternate with dark biotite gneisses, and the characteristic banded aspect of the mostly west-dipping gneisses is very widespread (Ph. 54). The light coloured granitic augen gneisses consist of orthoclase, as more or less stretched porphyroblastic augens. Oligoclase-albite forms an equal amount in the more fine-grained groundmass, together with irregular quartz and bands of biotite. The latter can be concentrated in thick layers with feldspars, as sedimentary biotite gneisses. About 15 km south of Kangchendzönga, on the west face of Pandim Peak, GARWOOD (1903) found bands of lime-silicate rocks rich in garnet and interbedded in mica schists. It is surprising that HOOKER noted these intercalations as long ago as 1854, a tribute to the powers of observation of this early explorer.



The Kangchendzönga gneisses, forming a regionally northwards-dipping synclinorium, are covered on the Jongsang Peak and further north on the Dodang-Nyima Peak by calcareous sediments (Dodang series of DYHRENFURTH, 1931). It is DYHRENFURTH's merit to have stressed these facts. His interpretation, however, of a reversed sedimentary section with Cretaceous beds thrust over the gneisses, was contested by AUDEN (1935), and was furthermore disproved by fossiliferous horizons in the Tso-Lhamo region. DYHRENFURTH's thrust line, resembling, according to him, the Alpine *Lochseitenkalk*, can be ex-plained by the lithological difference between gneisses and calc-schists sharpened by weathering and disharmonic movements. His sample with a doubtful *Innoceramus* from Dodang peak, kindly placed at my disposal, is actually a dense greenish silty limestone with a marked conchoidal fracturing, but no trace of a fossil. It seems more logical to compare the calcareous top section of the Jongsang Peak with the Everest limestones.

Northeastern Sikkim

Towards the *northeastern Sikkim* we distinguish, following AUDEN who investigated the Sebo-Chu Valley (1935), a wide basin-like zone of biotite-augen gneisses underlain by paragneisses and schists. Towards the border range with Tibet, augen gneisses and paragneisses alternate frequently, giving the steep southern rock faces a banded appearance. This banded zone forms the impressive range of peaks, such as the Pauhunri, Kangchengyao and Chomoyummo, which extend westwards over Chorten Nyima-La to Dodang Nyima Peak and connect with the Jongsang Peak north of Kangchendzönga. Most show a rather abrupt southern face and relatively gentle northerly dip slopes, where the sedimentary cover of Tibet begins. The range closes the northwards-directed domal uplift of Sikkim in an impressive and well displayed manner (Fig. 116).

On these southern faces at the head of the Sebo-Chu, AUDEN observed sills, dykes and smaller masses of white, rather fine-grained *tourmaline granites*. They strikingly resemble the young post-orogenic granites which we have already mentioned in the Badrinath and Everest region and which we will meet again in northern Bhutan. They consist of biotite and muscovite, oligoclase, orthoclase and tourmaline. The tourmaline can often be concentrated in spherical clusters with

Fig. 116 *The border range in NE Sikkim* SE of Pauhunri; drawn after photo by T. E. BRAHAM (Him. Journ. Vol. XVI, 1950) note the north-dipping well-bedded gneisses with local recumbent folds and young aplite-granite intrusions (J. B. AUDEN, 1935)

a biotite-free reaction rim. Some lime-silicate bands were observed within the paragneisses. The thin and extensive granite sills are surprising, and add to the banded appearance of the rock slopes. We will observe the exact replica of this feature in the southern rock face of Chomolhari (in northwest Bhutan). In the Sebo-Chu, as in all other regions, the tourmaline granites are unaffected by orogenic movements, except for some fracture cleavage, and they cut through all other rocks. AUDEN reports some flat-lying folds with northwards-dipping axial planes in the banded gneisses, cut discordantly by granites.

In the headwaters of the Lachen River, the northern continuation of the Tista which cuts through the main range, lies the beautiful Tso-Lhamo (Lake Goddess). This locality and the nearby Lachi Hills have become famous since HOOKER reported the first find of fossiliferous limestones. The area was later investigated by WAGER and subsequently by AUDEN (Fig. 111). According to WAGER (1939) the gneisses of the High Himalayan ridge south of Lachi are directly overlain by shattered fine arenaceous grey limestones, not unlike the main Everest limestone. The contact is formed by a 45° northwards-dipping fault zone. A similar shattered bluish limestone and associated shales were found by AUDEN on the northeast slope of Pauhunri, directly overlying the gneisses, and he also compared this limestone to the Everest carbonates.

These limestones, which can intermittently be traced westwards into the Everest region, are overlain by quartzites, silts and shales, followed by a thin limestone band with corals and small gastropods. Then come more than 150 m of pebble beds which AUDEN compares with the Gondwana Talchirs or the Himalayan Blainis. This fact is of greatest significance, since it indicates that the Gondwana facies, known already from the southern foothill belt, has reached northwards into southern Tibet (see also Fig. 144). The relatively rare pebbles are found in a dull green-brown grit, composed of ungraded angular quartz grains with feldspars, sericite paste and mica. The pebbles, with a maximum diameter of 10 cm, are mostly quartzites, with some pink limestones and rare muscovite granite. The pebble bed grades into calcareous sandstones, which are rich in Upper Permian brachiopods. Pebble beds and sandstones have been called by WAGER the *Lachi series*.

The Lachi series is followed by gritty sandstones with some plant remains covered by conspicuous dark grey limestones and shales, in which AUDEN (1935) found a rich ammonite fauna of Middle Triassic age. AUDEN called this important section the *Tso-Lhamo series* which falls between the Gondwana rocks and the widespread Jurassic deposits of Tibet.

East of Pauhunri Peak, the contact of the crystalline with the overlying sediments swings southeastwards, and can be followed into the *Phari plain*, where it was investigated by HAYDEN (1907). His excellent survey remains the only information so far available. Unfortunately, HAYDEN was not able to devote the necessary time to geological investigations, being attached to YOUNGHUSBAND's military expedition to Tibet. This was particularly true in the Chumbi region, although he was able to devote more time to the Kampa Dzong area.

West of the *Phari plain*, the gneisses of northwestern Sikkim are overlain by phyllitic slates and schists with flaggy, often crystalline calcareous bands. HAYDEN called this unfossiliferous formation *Khongbu series*. They have been correlated with the Everest pelites, but, except for the limestones, could also be compared with Daling-type sediments.

The Khongbu pelites overlie the gneisses or as along their southern border, seem to be in contact with the Chumbi granite—a foliated biotite granite apparently not belonging to the youngest granitic intrusions. The eastern contact coincides with a marked north-south-directed fault, the *Dothak fault* of HAYDEN, which brings the younger Mesozoic sediments of the Phari region east of the fault in contact with the Khongbu phyllites.

Just east of Dothak, limestones with quartzites, slates and shales form the ranges separating the upper Chumbi Valley from Bhutan. Dipping to the northwest, they are bordered by the Chumbi granite towards the south, which produced contact metamorphism and is thus of Mesozoic or younger age. Badly preserved ammonites and some bivalves were found, but are even generically indeterminable. Similar fossils were reported from calcareous horizons south of Peme-La (Tremo-La) on the Bhutan side of the range. They may be connected with the Mesozoic synclinorium discovered by the author in northwestern Bhutan, to be discussed in a later section.

South of Phari Dzong, above the Dothak series, follow mostly calcareous beds with some shales and quartzites containing fossils of probable Lower Jurassic age. Based on this fact, HAYDEN suggests a Triassic age for his Dothak series, since they are covered by the widespread calcareous deposits beginning with the Lias. The Mesozoic beds dip regionally northwestwards, and further north, along the Bhutanese border, more to the west. They thus outline a marked south-directed embayment of Tibetan Mesozoic sediments, bordered to the west by a fault zone, to the east by eastwards-rising older beds, and eventually crystalline rocks. This *Chumbi Valley basin* forms the *southernmost outcrop* of the Tibetan Tethys facies along the whole Himalayan range. It also coin-

cides with the section of the Himalayas where Tibetan territory reaches furthest towards the Indian plains (see also Fig. 145).

Jurassic, Cretaceous and Eocene of southern Tibet

HAYDEN has followed Jurassic calcareous beds from the northwestern side of Chomoyummo, still belonging to the granite and gneiss region of north Sikkim, to the famous hills of Kampa Dzong, and collected a fauna with Middle (Lungma limestones) to Upper Jurassic affinities, including many forms from the Spiti shales. Jurassic beds were observed all along the route from the Phari plain to Gyantse, and further on to the Tsangpo River, south of Lhasa.

An interesting region is crossed south of Gyantse, about half away between Phari Dzong and the Tsangpo. In a tectonically disturbed zone of Jurassic sediments are intrusions of hornblende granites, similar to the Kyi-Chu granites of Lhasa. The same area is characterized by numerous *basic intrusions* in the form of dykes of amygdaloidal diabases, altered diorites, norite gabbros and serpentine lenses. The basic rocks form an extensive belt striking roughly from the WNW Shigatse region, towards the large Yamdrok-Tso (Lake) in the east. An incipient metamorphism can be noted along this belt in the Jurassic sediments, altering them to slates, phyllites and calc-schists. Such incipient metamorphic rocks form the highest mountain group in this region, the 6700 m high Nöjinkangsang, according to HAYDEN the most conspicuous landmark. He noticed granite boulders in the valley which must have come from the higher mountain region. This meta-

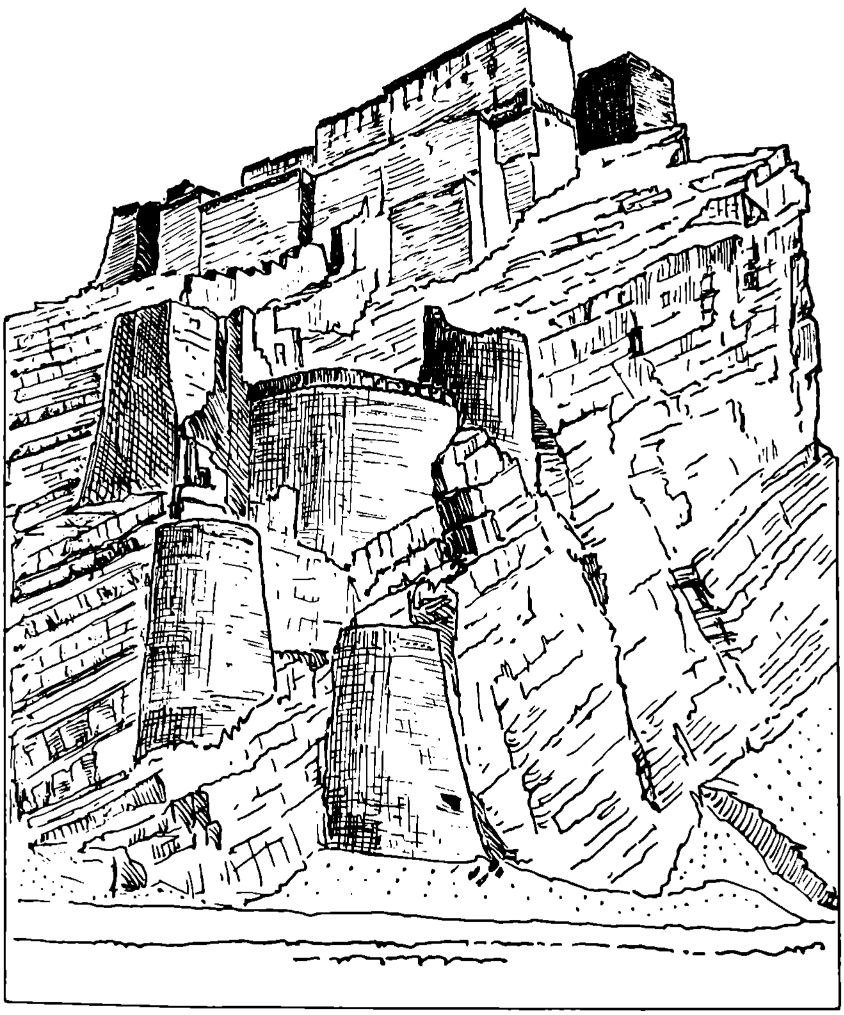


Fig. 117 *Kampa Dzong, S Tibet,* the type locality for the Upper Cretaceous Kampa limestones. The Dzong sits on well-bedded Cretaceous limestones; drawn after photo in H. RUTTLEDGE, Everest (1934)

morphic region is indicated with red hatches on the geological map (Pl. I A). Since similar dykes are known to intrude into Cretaceous sediments in the Kyi-Chu Valley south of Lhasa, their age is mostly late Cretaceous or early Tertiary. From the still rather vague facts of HAYDEN's traverses it seems quite relevant that this incipient metamorphism with basic intrusions coincides with tectonic disturbances. The wide and rather uniformly distributed Jurassic beds, which when affected by regional metamorphism are not unlike the Alpine *Bündnerschiefer*, representing the deepest Alpine basin fill ("Eugeosyncline" with ophiolites), may after all indicate somewhat similar conditions in this part of southern Tibet, and we may even be not too far off in considering this region as an eastern extension of the ophiolites observed further to the west, without, however, the tectonically severely affected zone—the geosuture of the Indus Flysch belt.

The *Cretaceous and Lower Tertiary* sediments of this part of southern Tibet have been described by HAYDEN as *Kampa system* from the type locality Kampa Dzong, situated approximately 20 km north of Tso-Lhamo. The Cretaceous ridge of Kampa Dzong can be followed along its ESE strike until the plain of Phari Dzong, where it merges into a hilly zone over 20 km wide. At Kampa Dzong, HAYDEN has distinguished the following sequence, included in Fig. 111. The Cretaceous begins with a basal unfossiliferous limestone (the *Giri limestone*) which follows directly above the here somewhat Flyschy Spiti Shale representatives. It is overlain by the Cenomanian *Kampa shales* and the *Kampa limestones*, consisting of two main limestone scarps, on which the famous Kampa Dzong (monastry fortress) is built (Fig. 117), and finally topped by a more shaly limestone section of Maestrichtian age called the Tüna limestones. The second limestone, rich in rudists, represents the Senonian.

The upper part of the Kampa section, forming a pronounced ridge, represents the *Eocene*. The contact with the Cretaceous is rather sharp, made conspicuous by an intercalation of gritty ferruginous sandstones. No unconformity has been noted. Above and again with a sharp contact follows a first limestone, thin-bedded below, but mostly thick-bedded to massive towards the top. Separated by shales and nodulous shaly nummulitic limestones we find a second limestone with *Operculina*. This is divided by *Spondylus* shales from higher *Operculina* and topmost *Alveolina* limestones. The youngest Eocene beds exposed are the *Dzongbuk shales;* all younger deposits are hidden beneath a wide plain covered by Plio-Pleistocene gravels.

Cretaceous and Eocene formations were again observed more to the west by HERON (1922) north of the Everest group. Folding and local thrusting is here severe, and much of the fossil content has been destroyed (Fig. 118). The same lithological sequence can be observed as in the Kampa region. The Cretaceous forms east-west-directed, steeply folded, mostly south-vergent structures, with Eocene rocks preserved in two areas, in the Tspri ridge and in the more western Yaola region. Here too, ferruginous sandstones form the contact between the Cretaceous and the Eocene. On a sharp ridge of northwards-dipping Cretaceous beds is located Shekar Dzong, a well known landmark for the Everest expeditions with the Tibetan approach (Fig. 119).

The Cretaceous with its relic Eocene synclinal outliers occurs in a wide depression, drained by the Phung Chu—the head waters of the Arun River. To the north of this depression HERON mentions a higher range, called locally the Northern Range. It consists mainly of Jurassic beds showing signs of an incipient metamorphism which locally can reach a relatively high grade, as witnessed by the formation of staurolite in phyllitic schists. Garnet schists and hornblende garben schists, though not in situ, were reported. Within these more metamorphic Jurassic formations occur intrusions of massive light-grey and fine-grained biotite-muscovite granites, rich in orthoclase and rather poor in plagioclases. They differ from the tourmaline-bearing young Makalu granites by the lack of tourmaline, and from the Kyi-Chu granites of HAYDEN by the absence of hornblende and the reduced amount of plagioclase. In spite of the absence of tourmaline, these light-grey, massive types of fresh granites could most likely correspond to the Makalu-type granites, which have been observed as far north as the Rongbuk Valley north of Everest.

The metamorphic belt with granitic intrusions of the so-called Northern Range of HERON could be compared with the metamorphic Jurassic belt already observed by HAYDEN south of Gyantse, and mentioned above. It may be a separate, more southern zone, or the southern part of a much larger main zone which in this case would correspond to a *metamorphic Jurassic belt of great dimensions and of regional importance.*

Kyi-Chu granite

Granitic intrusions, which we have already noted south of the Tsangpo are widespread along the Kyi-Chu from Lhasa to its junction with the Tsangpo. Called Kyi-Chu granites by HAYDEN (1907), they expose intrusive contacts with Cretaceous sediments which outcrop to the north, west and southwest of Lhasa.

The similarity of the *Kyi-Chu granite* with the *Kailas granite* was already alluded to in the chapter dealing with the northern Kumaon Himalayas. According to HAYDEN, the Kyi-Chu is a rather

uniform hornblende-biotite granite. It occurs in two varieties, a coarser one richer in quartz, and a finer type with more ferro-magnesian minerals and grano-dioritic affinities. Albite frequently accompanies some oligoclase, orthoclase and microcline. A very constant and rather frequent accessory is the sphene, already noted in the Kailas granites. It increases in the more grano-dioritic varieties which also show a rather high content of epidote and even free calcite, presumably assimilated from the surrounding Cretaceous and Jurassic calc-schists. The granites are generally massive, and differ from the often foliated Himalayan granites. Basic *schlieren* are particularly rich in hornblende. The presence of augite, as sieve-like inclusions in the hornblende typical for the Kailas hornblende granites (Ph. 32), is not reported by HAYDEN. He rightly stresses the difference of the Kyi-Chu granites from the probably older foliated biotite granites and granite gneisses of the Himalayas as well as the youngest tourmaline granites.

Little is known of the extension of the Kyi-Chu granite, other than its presence north of Lhasa and along the Kyi-Chu as well as north of the Tsangpo above the junction of these two rivers.

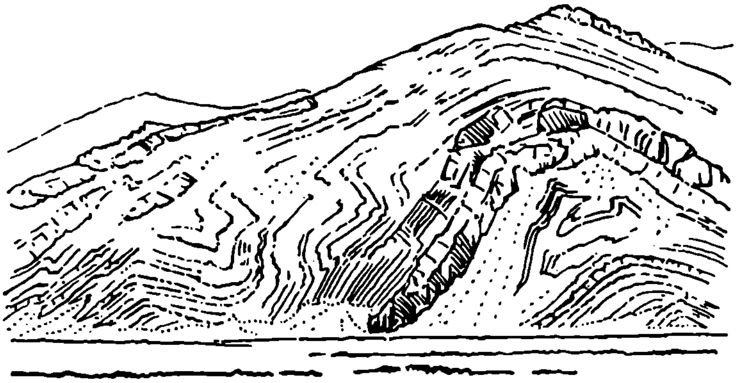


Fig. 118 *Disharmonic folds in Upper Cretaceous Kampa shales and limestones,* near Dzakar-Chu, W of Kampa Dzong S Tibet; drawn after photo by A. M. HERON (1922)

HAYDEN was struck by the abundance of dacitic pebbles in the Tsangpo River gravels above the confluence with the Kyi-Chu. He believed that the dacite represents a more effusive facies of the Kyi-Chu granites. While this may be so, their relation may actually be more indirect, since I believe that most of the Tsangpo pebbles are derived from the Kailas conglomerate, which must have a rather wide extension in the head waters of this river.

BHUTAN LOWER HIMALAYAS

For a general outline of the structural features and the local nomenclature we refer to Fig. 147 and to the section B and C on Plate II.

All along the Siwaliks of the Bhutan Sub-Himalayas the Main Boundary Fault is well developed. To the north of it the Lower Hima-

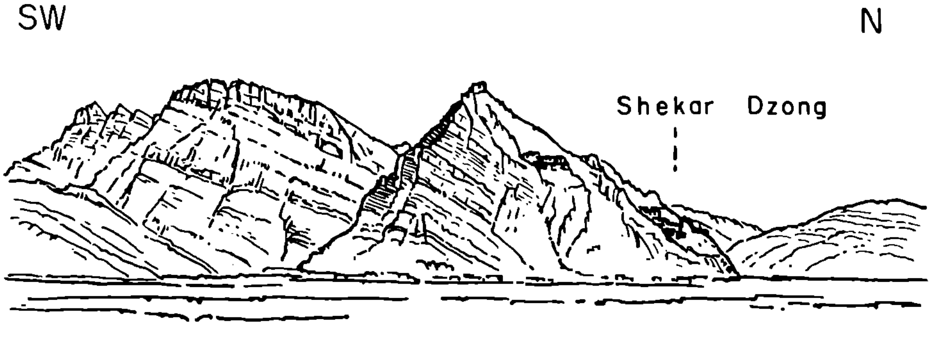


Fig. 119 *Shekar Dzong,* on a northwards-dipping ridge of Upper Cretaceous limestones. S Tibet; drawn after photo by TILMAN, Everest (1948)

layas consist, depending on their structural configuration, of Gondwanas (Damudas), Baxas or Daling-type sediments and their respective metamorphics. Local stretches of the foothill belt are relatively well known, such as the Bhutan Doars, already investigated by MALLET (1875), and again the area around the Baxa[1] fort studied by LAHIRI (1941). In eastern Bhutan PILGRIM (1906) made a short reconnaissance in the foothills east of Manas River.

Recently the Geological Survey of India has undertaken detailed investigations in the Baxa carbonate rocks, though no official report has been published so far. No information was available about the complicated hinterland of the Lower Bhutan Himalayas, and the author's recent investigations merely provide a first rough appraisal of this virgin geological territory.

Before discussing the actual Lower Himalayan rocks we may draw attention to a peculiar outcrop of amphibolitic schists discovered by MALLET in the Raidak (Wong-Chu) River. This outcrop was met *south* of the Main Boundary Fault and even south of the first Siwalik sandstones. MALLET writes (1875, p. 44): "Proceeding up the left flank of the Raidak River, the first rock met with is hornblende schists in thick beds dipping north 10° west at 50°, and forming a low eminence; only a small thickness is seen. Beyond this is blank for a couple of hundred yards, and then Tertiaries come in, dipping locally to north at 80°. There can hardly be a doubt that this rock belongs to the gneiss which forms most of the hills that are scattered over the alluvial valley of the Brahmaputra, and which, according to Mr. Medlicott, there is no reason to suppose is distinct from that of Bengal."

According to MALLET's description it is unlikely that this outcrop is merely a large boulder. Moreover no similar amphibolites are known in the neighbourhood, except for some sills and dykes of diabasic epidiorites, and these, in the form of large blocks, were known to MALLET. Should MALLET's conclusion be right, we have the only known locality of the Himalayan front where Peninsular shield rocks outcrop in the foothills, just to the south of, or within, the Siwalik belt. The questionable outcrop nearly coincides, however, with the narrowest stretch of the Himalayan foreland, where the Quaternary-covered basin is only 35 km wide (Inselbergs north of the Brahmaputra River). A detailed investigation of this outcrop may yield additional information. The writer does not know whether the recent foothill studies by the Geological Survey have confirmed this peculiar occurrence.

Gondwanas (Damudas)

Gondwana sediments resembling the Damudas of the Darjeeling area have been reported by LAHIRI (1941) from the foothills southeast of Baxa Fort where they abut against the Main Boundary Fault, and PILGRIM (1906) described them from the Kala Pani and Devangiri in eastern Bhutan. Southeast of Baxa, in the Jainti Hills, the detrital Gondwana rocks form a thin band, not more than 70 m wide, dipping steeply northeastwards. Gritty sandstones with subangular grains of quartz and feldspars are frequent, locally becoming quartzitic and calcareous towards the top. Thin lenses and layers of graphitic shales and anthracitic coal are included in the sandstones. Downwards the sandstones are more carbonaceous and softer, with veins and nests of calcite. The coals show the typical low volatile content and a relatively high amount of fixed carbon. In eastern Bhutan PILGRIM found soft fine coal-bearing sandstones forming the deepest outcrops, followed upwards by more quartzitic sandstones. The total thickness observed is 170 m. PILGRIM, in his Kala Pani section, depicts a steep northwards-dipping anticline, thrust steeply on the Siwaliks which show a more gentle dip than the overthrust Gondwana rocks. In both areas the lower and upper contacts of the Gondwana rocks are highly sheared, with conspicuous slickensiding. The generally soft Gondwana outcrops are frequently masked by scree and their original extension is probably considerably larger than can be deduced from the scattered outcrops.

Baxa Series

MALLET (1875) named a quartzite, shale and dolomite sequence falling between the Gondwanas or Siwaliks and the Dalings *Baxa series*, after the old Baxa Fort in the western Doars. They are not known along the Sikkim foothills, but set in approximately with the western border of Bhutan, and seem to occur intermittently all along the foothills. They were recorded again in the lower Manas River and Kuru-Chu by PILGRIM (1906) from where they seem to follow approximately the course of the Manas River towards the Tashi Gong region of easternmost Bhutan. Their eastern continuation into the foothills of the NEFA Himalayas is questionable. Thin bands of Gondwana rocks have been variously reported, but their northern border seems to belong to the Daling-type rocks or even higher metamorphics and not to the Baxas. The latter

[1] Baxa and Buxa are both in use. MALLET (1875) speaks of the Baxa series, but has Buxa on his map. LAHIRI (1941) calls it Buxa, WADIA (1957) again Baxa and KRISHNAN (1960) Buxa. We follow the *Stratigraphical Lexicon* which refers with no alternative to Baxa series.

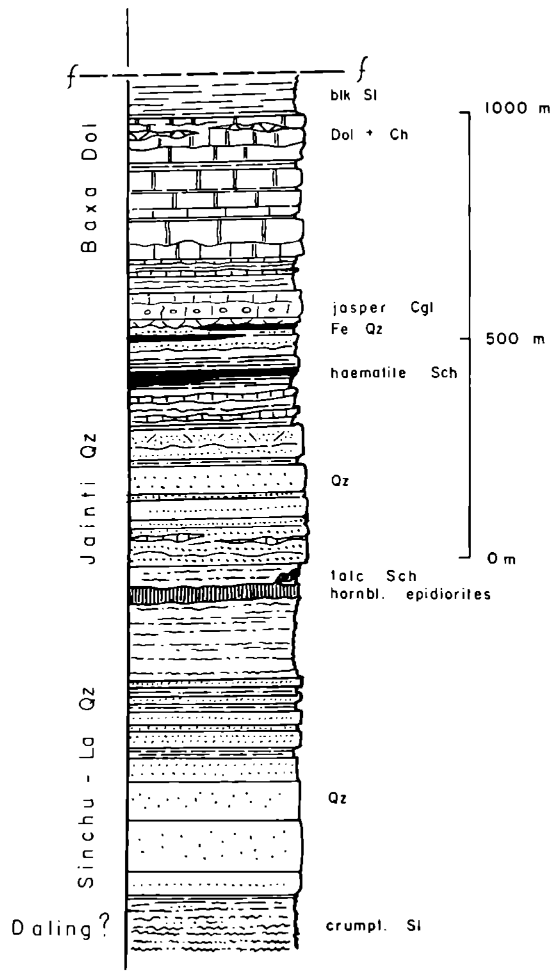


Fig. 120 *Stratigraphy of the Baxa series.* South Bhutan Himalayas; compiled after MALLET (1875), PILGRIM (1906) and LAHIRI (1941)

should also be distinguished from the newly discovered sedimentary zones in the central part of Bhutan.

Based on the information of MALLET, PILGRIM and LAHIRI, I have compiled a tentative stratigraphical column (Fig. 120) of the Baxas from the Bhutan foothills. Our own investigations along the lower road section beginning in Phuntsholing have shown that most severe tectonic disturbances occur, and that a sharp division between Baxa and Daling formations is practically impossible (Fig. 123). Only the lower Baxa section seems to outcrop along this part of the foothills. It is therefore questionable to what extent we have to deal with normal sequences, how much of the outcropping profiles is normal or reversed, and how much is repeated by imbrication and faulting. Our preliminary stratigraphical sequence begins with crumpled shales, slates and schists, grey to greenish and locally quartzitic. They may still belong to the Dalings. With a rather sharp contact follow thick-bedded to massive quartzites. They are fine to medium-grained, mostly light-grey to greenish and feldspathic in the lower layers. Upwards they become thinner bedded and show ripple marks. Towards the top argillaceous intercalations increase and lead to the siliceous slates and phyllites, which locally can show signs of increasing metamorphism. Sills and dykes of amphibolitic epidiorites are frequently met in the upper part of this argillaceous section, forming the base of a next quartzite horizon. LAHIRI (1941) places the lower quartzites and covering phyllites into his *Sinchu-La* stage.

The next higher quartzites are well exposed along the Jainti River, and are accordingly called the *Jainti quartzites.* They form the base of the true Baxa series. A conspicuous band of greenish talcose schists marks their contact with the Sinchu-La beds. The flaggy quartzites become more thick-bedded towards the top. They contain copper ores and some pyrite, often staining the rocks rusty brown. The highest layer is fine-grained and of a more cherty aspect. It is followed by variegated, mostly pink, brown and greenish calcareous shales and thin quartzites. Lenses and pebbles of red jasper are frequent in some of the limestone bands. Conspicuous haematite quartzites and schists also occur, locally capped by residual iron ores. Some of the iron ore occurs in thin bands, alternating with very fine-grained cherts and jaspers. The haematite quartzites, still banded, form more massive layers. These banded iron ores have been compared with the characteristic Precambrian iron ores of the Peninsular shield, but the recent investigations of O'ROURKE (1962) suggest that many banded iron deposits of the Himalayan foothills are probably of Permo-Carboniferous age. If this is true a Permo-Carboniferous age could be suggested for the whole Baxa series, but this possibility, favoured by O'ROURKE, is still open to much doubt.

The most conspicuous part of the Baxas, however, are the carbonate rocks overlying the ferruginous horizons. They consist of several dolomitic limestones and thick dolomite layers. The lower dolomite horizons are light-grey and thick-bedded, while the upper horizons are thinner, dark grey and often of a sacharoidal aspect. A slight mineralization by galena and sphalerite has been noted in the lower layers (LAHIRI). The carbonates are practically free of siliceous impurities. The uppermost dark slates are cut off by the thrusts which carry the older Daling phyllites and schists over the Baxa outcrops. In western Bhutan the dolomites are well exposed and form conspicuous ridges west of the Torsa River (Fig. 121) and again west of Baxa

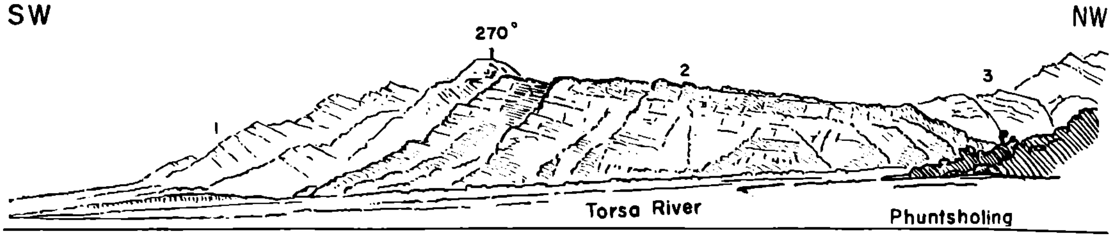


Fig. 121 *The dolomite scarp west of the Torsa river.* Baxa series, SW Bhutan; original by A. GANSSER

1 phyllites and slates 2 Baxa dolomites 3 Daling schists and quartzites

Fort. They are, however, not continuous and are tectonically disturbed.

In the eastern Bhutan foothills the stratigraphical sequence is similar. PILGRIM (1906) describes, however, much larger sections of quartzites, reaching a total of 3000 m, a figure too large and most likely resulting from repeated imbriations. His traverse from the Manas River to the Kuru-Chu is reproduced in Fig. 122. He shows the uppermost limestones in a synclinal

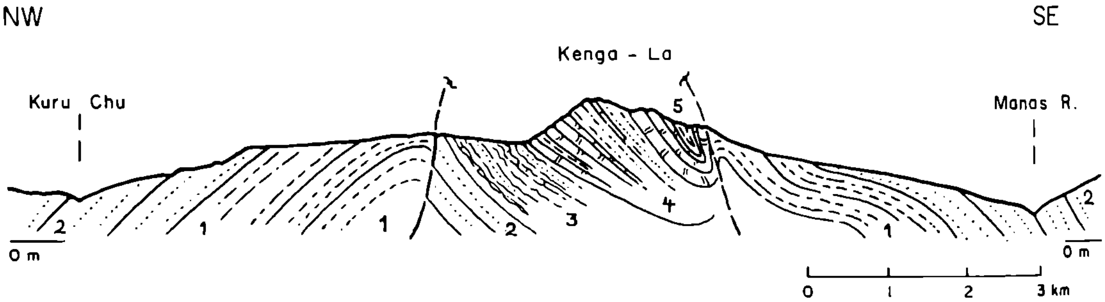


Fig. 122 *Section across the Kenga-La,* between Manas River and Kuru-Chu. SE Bhutan; after G. E. PILGRIM (1906)

1 greenish schists and slates, Daling
2 massive quartzites } Baxa
3 calcareous slates with thin quartzites } Baxa
4 slaty dolomites with quartzitic schists } Baxa
5 dolomites } Baxa

Phot. 54 *The impressive SW flank of Kangchendzönga* (8585 m), with the head of the Yalung Glacier and valley. The clearly bedded augen gneisses and granitic gneisses rise towards the E over the Sikkim dome (phot. Indian Air Force; copyright Swiss Found. Alp. Res.)

Phot. 55 *Highly disturbed slaty phyllites,* subfolded with south vergent folds and cleavage. Lower Baxa and Daling. Zone of thrusting in foothills of SW Bhutan (phot. A. Gansser)

Phot. 56 *Fractured thin quartzites in sheared phyllites.* Highly tectonized thrustzone in foothills of SW Bhutan (phot. A. Gansser)

Phot. 57 *Steep, NW dipping thrust zone* with drag folds and secondary sheared zones in severely tectonized Daling schists and slates of foothills between Phuntsholing and Kamij, SW Bhutan (phot. A. Gansser)

Phot. 58 *Strongly boudinaged quartzites* and white vein quartz, surrounded by phyllites in tectonized quartzite section. Foothills north of Hatisara, SE Bhutan (phot. A. Gansser)

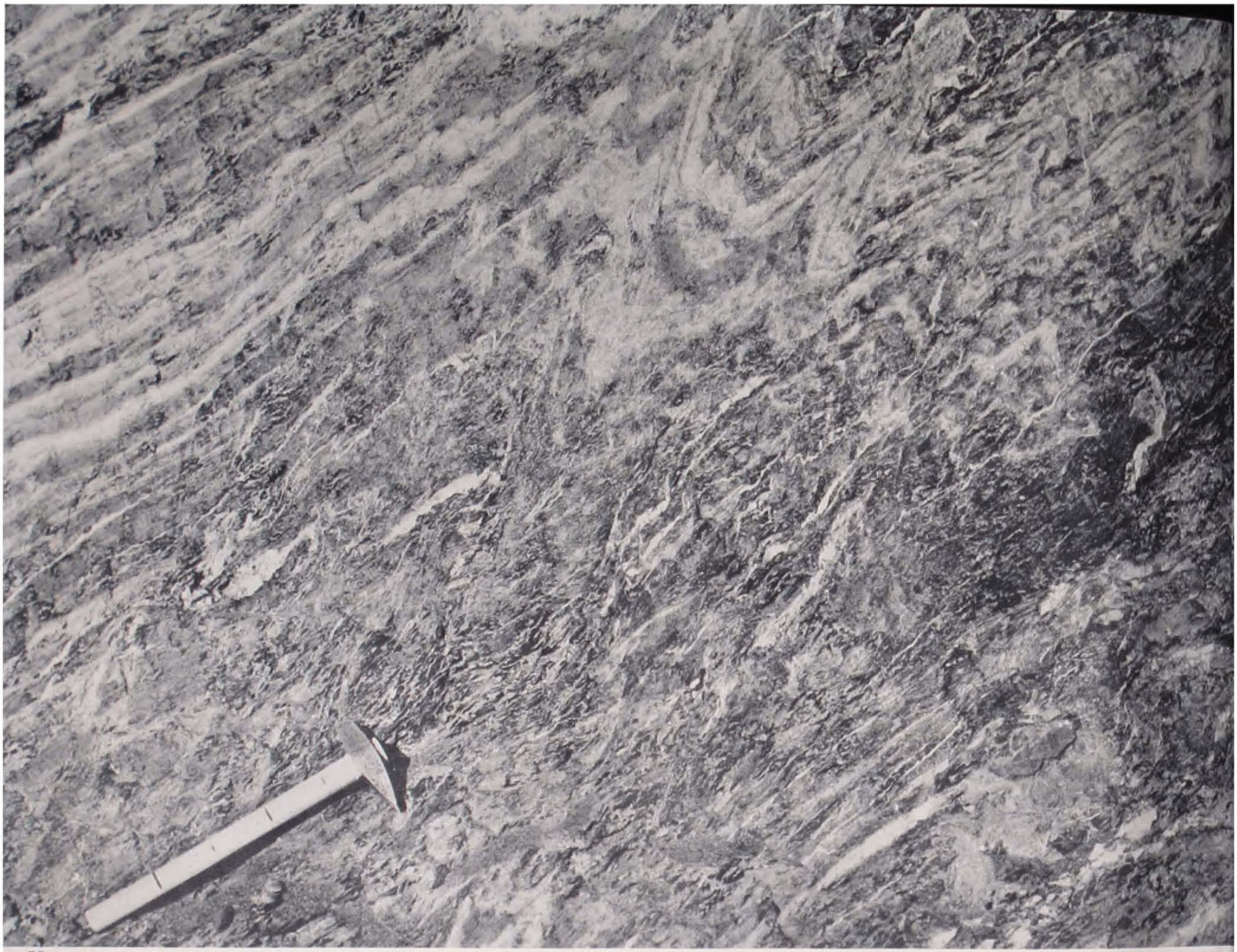
Phot. 59 *Steeply dipping, well-bedded quartzites* with a marked fracture cleavage and larger pinch-outs in quartzite section north of Hatisara, SE Bhutan (phot. A. Gansser)

Phot. 60 *Sheared, lenticular migmatitic biotite gneisses with aplitic zones.* Chasilakha gneiss. Lower part of large Chasilakha thrust mass. SW Bhutan (phot. A. Gansser)

Phot. 61 *Intensely subfolded migmatitic biotite- (muscovite)-gneisses* with shear zones and aplitic bands. They form regionally massive horizons within the Chasilakha thrust sheet. SW Bhutan (phot. A. Gansser)

Phot. 62 *Banded granitic biotite-muscovite gneisses* with aplitic (to pegmatitic) dykes characterized by diffuse borders. The dykes follow zones of tectonic dislocations. Suraya gneisses, SE Bhutan (phot. A. Gansser)

Phot. 63 *Coarse muscovite-garnet pegmatites,* profusely intruding biotite (kyanite) schists. Suraya crystalline, SE Bhutan (phot. A. Gansser)



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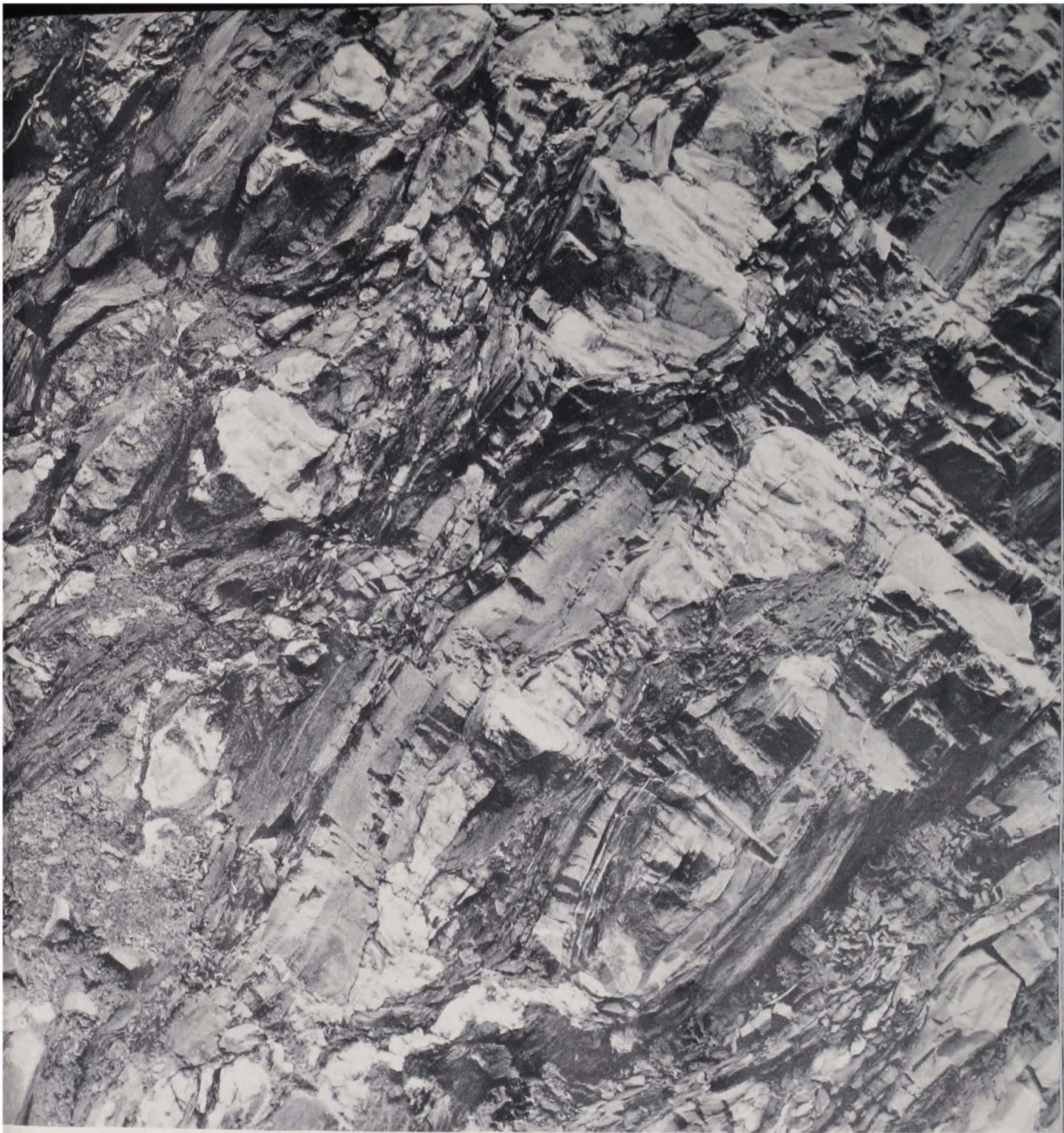

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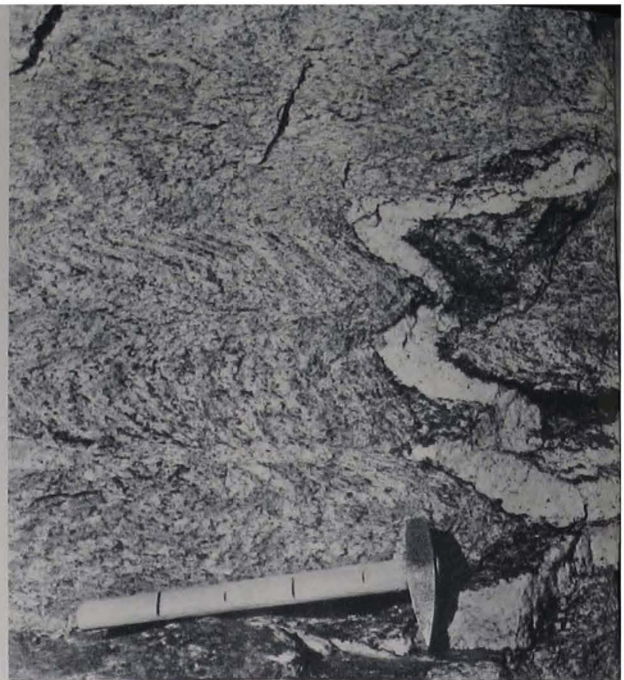
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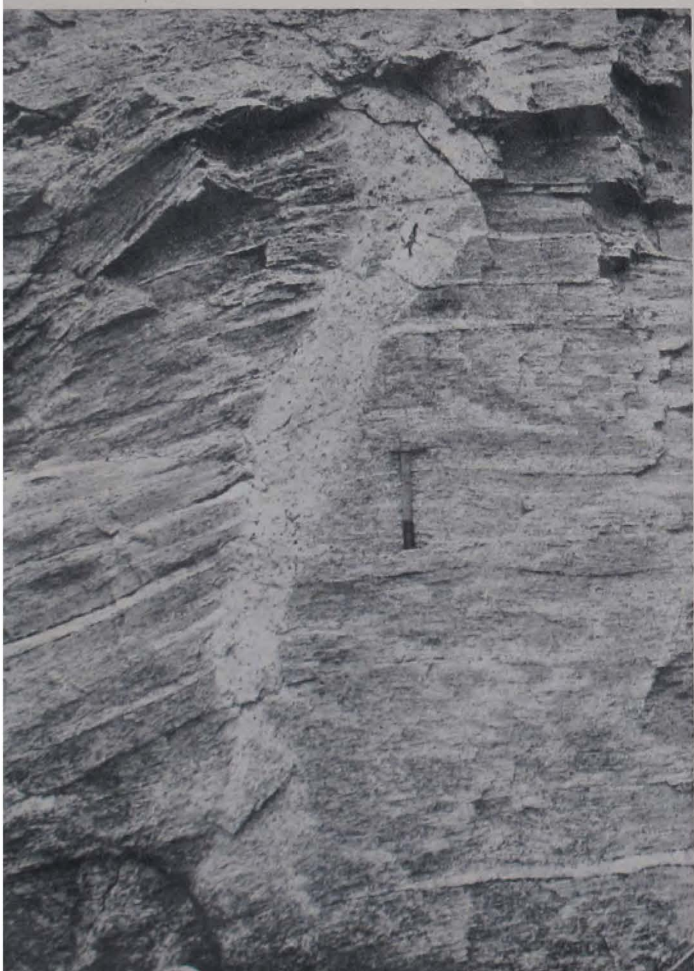
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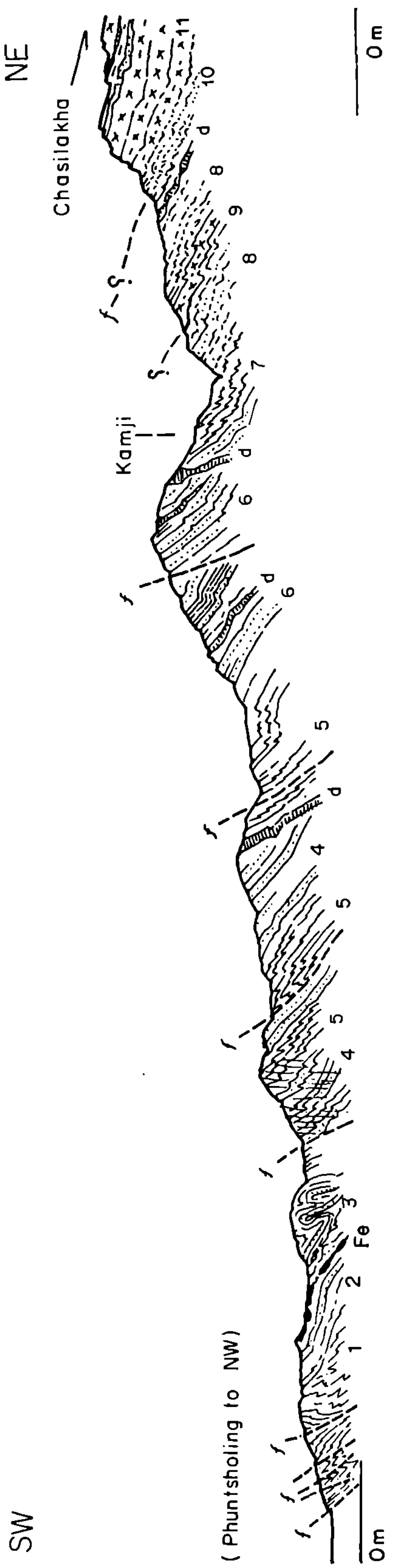


position and with fault contacts on the Kenga-La. The Jainti quartzites of the Baxa region are less developed, while the Sinchu-La quartzites are considerably thicker. Gypsum deposits from this region have recently been investigated by the Geological Survey. The greenish and grey phyllitic slates underlying the quartzites of the Manas and Kuru-Chu Rivers have been correlated by PILGRIM with the Darjeeling Dalings. LAHIRI includes his Sinchu-La as a lower stage, the Baxa as an upper stage of the Daling series. While the lower quartzitic and argillaceous Sinchu-La deposits are similar to the Dalings except for the excessive amount of quartzites, the Baxas with their characteristic carbonate rocks *should be clearly separated from the Dalings.* It is still questionable if they should be correlated with the Krols or with the Deoban-Tejam belt of the Kumaon Lower Himalayas. I would prefer the latter alternative, but must admit that such a long-distance correlation is more than questionable.

Lower Baxa and Daling-type rocks northeast of Phuntsholing (SW Bhutan)

The new road section crossing the foothills of western Bhutan from Phuntsholing to the northeast exposes rocks somewhat resembling the quartzitic and argillaceous part of the Baxas. On the other hand they show some affinities to a rather complex Daling sequence. Because of the extreme tectonization of this section even a detailed survey would not give conclusive results. Our own investigations, of a reconnaissance nature, must be interpreted accordingly. For better reference a tentative section is included from the plain of Phuntsholing to the gneiss masses of Chasilakha (Fig. 123).

The hills just above the flood plain expose highly sheared, contorted and faulted slaty phyllites with silty bands, mostly dark grey to greenish grey (Fig. 124). Phyllonitic horizons are nearly black and often strongly slickensided. A strong

Fig. 123 *Section across the SW Bhutan foothills* (Phuntsholing-Chasilakha); original by A. GANSSER

1 strongly sheared slaty phyllites
2 red claystone with hematitic schists
3 ferruginous quartzites with red and green shales
4 dark grey phyllonites and sheared quartzites
5 green and violet slaty phyllites with cherty quartzites
6 thick-bedded white quartzites with sericitic and talcose partings (Cu ore)
7 folded schistose phyllites
8 sericite schists and quartzites
9 sheared augen gneiss
10 biotite-sericite schists
11 biotite-granite gneiss (Chasilakha zone)
d hornblende diabases

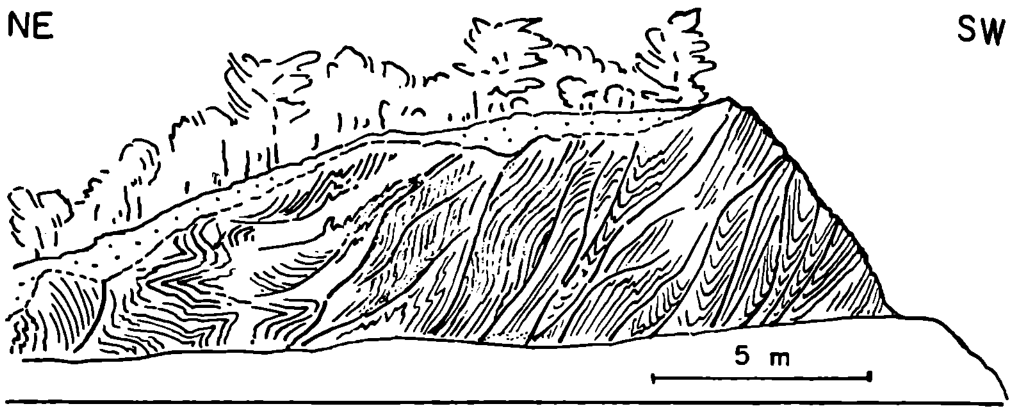


Fig. 124 *Highly sheared slaty phyllites and phyllonites in the thrusted foothills of SW Bhutan,* above Phuntsholing (1 of fig. 123); original by A. Gansser

pressure cleavage and minute drag folds are the effect of a strong tectonization. The larger folds are overturned towards the southwest, and their near-horizontal fold axes strike NW-SE (Ph. 55). Locally occur thin, fine-grained quartzitic layers which are highly fractured and disconnected within the sheared phyllitic masses (Ph. 56). Larger thrust zones are invariably steep, dipping to the NW (Ph. 57). All the evidence indicates a *most severe tectonization* which may be related to the thrust contact of the Baxas with the Daling slates. Continuing along the road section one observes reddish mudstones and shales with haematitic schists and corresponding ferruginous caps separated from the phyllites by various local thrusts. These beds may represent the haematitic schists occuring normally below the calcareous Baxas (Fig. 120), though along our section an equivalent of the Baxa-type dolomites was not observed. We note, however, ferruginous quartzites with cherty horizons and green and red shales. This colourful section exposes an intense disharmonic folding, still with flat southeast-northwest-directed fold axes. The beds involved are unlike the Dalings and seem to represent the middle part of the Baxa. Further northeastwards a wild succession of faulted and thrusted slates and mostly white quartzites follows, the former intensely sub-folded, the latter fractured but more regularly bedded. Several steep thrusts can be

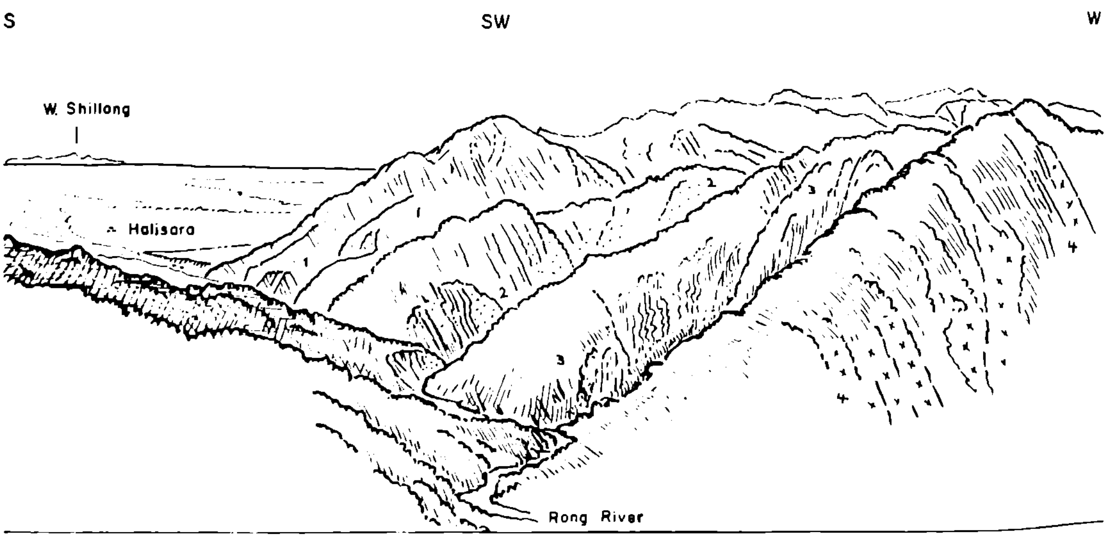
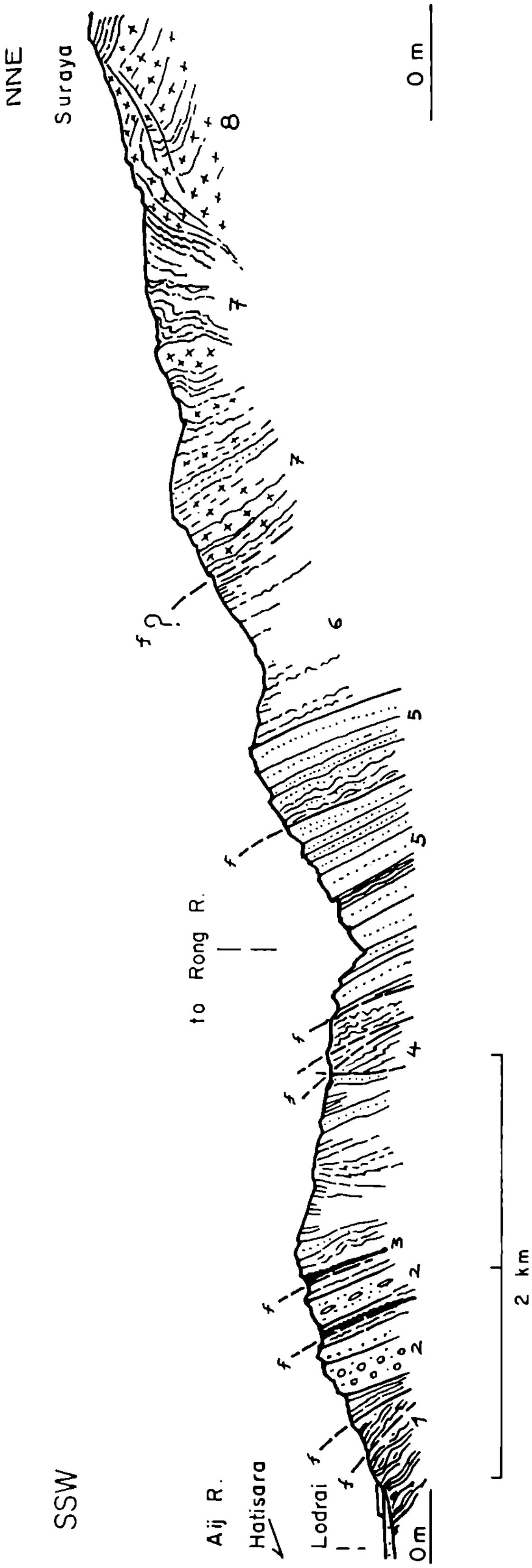


Fig. 125 *The foothills of Hatisara,* SE Bhutan. View into the Brahmaputra plain with the western Shillong shield rocks at the horizon; original by A. Gansser

1 phyllites, quartzites and quartz conglomerates
2 main quartzites
3 sericite schists
4 Surayà gneisses



assumed, but their magnitude is unknown since in this complicated section the stratigraphical sequence is not normal. Intercalated phyllites resemble the sheared section at the base of the foothills. Along zones of disturbance we note the first dykes of fine-grained diabases, increasing somewhat in abundance towards the northeast.

Towards Kamji the *quartzites* increase. They are white, fine-grained, thin to thick bedded with sericite partings. The intervening phyllites show an increased sericitization. Along the contact with the quartzites, which are generally disturbed, one notes green talc schists in some places. Thin diabase sills are also intercalated. Unfortunately no unmistakable indication for bottom and top determination in the quartzitic horizons was seen. Some cross bedding speaks for a reversed section of the Kamji quartzites, but the indications are not too conclusive. Above and to the northeast of Kamji sub-folding and shearing is again most intense in the argillaceous sections, now *gradually becoming more metamorphosed.* Sericite schists are formed, rich in irregular quartz veins. Within these tectonized sericite schists lies an *augen gneiss*, in itself sub-folded and sheared. The augen are formed by a perthitic orthoclase with myremekitic rims surrounded by a mosaic of small quartzes, some plagioclase and biotite rich in sphene and epidote. The gneiss seems tectonically emplaced. It differs, however, from the granitic gneisses following higher up in the section. Sericite schists above the augen gneiss lamellae show a gradual increase of biotite together with the formation of larger muscovites. Sericitic quartzite layers are still present. Finally still intensely folded biotite-muscovite schists occur, already reflecting a higher grade metamorphism. The biotite-muscovite schists are overlain conformably, though with disharmonic contacts, by well- to thick-bedded biotite-granite gneisses, which lead to the large saucer-like *crystalline mass of Chasilakha.* In spite of intense shearing and sub-folding of the underlying meso-metamorphic schists, no regional tectonic contact can be traced in the field between the argillaceous rocks and the overlying granite gneisses. Except for the strong tectonization, we see a certain similarity to the change of the Daling schists into the Darjeeling gneisses of Sikkim.

Fig. 126 *Section across the foothills between Hatisara and Suraya.* SE Bhutan; original by A. Gansser

1 highly sheared green and violet phyllites
2 red and green quartz conglomerates
3 black graphite schists, mylonite zone
4 green phyllites, Daling type
5 platy fine-grained white quartzites
6 sericite-biotite schists
7 augen gneiss, banded gneiss, sericite quartzites, biotite-schists
8 biotite granite-gneiss with garnets (Suraya gneiss)

Lower Baxa and Daling-type rocks north of Hatisara (SE Bhutan)

Returning from eastern central Bhutan we investigated the foothill regions north of Hatisara (Fig. 125). Road construction produced some excellent outcrops in this steep jungle-covered country. They are shown on a tentative section from Lodrai in the south to Suraya in the northeast (Fig. 126). The sediments, corresponding to Baxa and Daling rocks, form a narrow and steep belt, with a rather constant abnormal strike direction from NW to SE. It is therefore questionable if these foothill rocks can be traced into the already described section north of Phuntsholing in southwest Bhutan.

Greenish and dark violet highly sheared phyllites form the lowest foothill outcrops, covered by terraces of the Ai River near Lodrai road camp. They dip towards northeast and are overlain by most conspicuous *quartzitic conglomerates*. Pink and violet, white and dark-grey quartz and quartzites form pebbles varying from 1 to 5 cm. They are sub-rounded and covered by sericitic films. The matrix is coarse gritty and badly sorted, and rich in sericite and quartz. The conglomerate is indistinguishable from the slightly metamorphic Verrucano conglomerates of the eastern Gotthard massif in the Alps, but here we have to deal with much older, probably Cambrian or even older deposits. We may recall that similar conglomerates of an assumed Permian age have been mentioned by HAGEN and BORDET from Nepal (p. 148).

Northwards the conglomerates become intensely sheared and the quartz pebbles considerably stretched. They are bordered by conspicuous graphitic mylonitic shale zones. With steep northeastern and locally vertical dips follow greenish phyllites and thin quartzite bands. Some of the green Daling-like phyllites can assume a real flowing pattern in the highly tectonized zones. These are particularly frequent near the thick fine-grained quartzites following further northwards. The latter recall the Kamji quartzites of the Phuntsholing section, but here they are considerably thicker. Usually very well bedded with a quite constant dip of about 50-60° to the northeast, they contain intercalated horizons of phyllites surrounding strongly boudinaged quartzite and vein quartz lenses (Ph. 58). The quartzites are cut by a conspicuous cleavage system intersecting the steep bedding with mostly flat and some steeply southwards-dipping joints (Fig. 127). Locally large-scale pinch-outs, accentuated by some bedding cleavage, somewhat resemble large cross bedding. A dubious reversed sequence is indicated in this particular section (Ph. 59). The main quartzites are over 1000 m thick and form the very steep ridges in this jungled region.

With a rather sharp break the main quartzites are overlain by sericite schists, in which biotite increases gradually until real biotite schists are met. They still contain some thin sericitic quartzite horizons which remain surprisingly constant in spite of the change in metamorphic grade. Throughout the section the biotite schists are highly disturbed, particularly towards the first gneissose intercalation. Here again, a major disturbance may be present, but cannot be clearly seen in the field. The first gneisses are finely striated and banded biotite-muscovite gneisses, and certain horizons of typical augen gneisses are found. This whole gneiss mass, with intercalated biotite schists and some quartzites, will be discussed separately. It may correspond to the Chasilakha gneisses covering the Phuntsholing section, except that in our present area, the tectonic style of the crystalline mass is much more complicated and its overall dimensions are considerably smaller (Fig. 126).

Chasilakha gneiss zone

A conspicuous granite gneiss mass, mostly gently dipping and several hundred metres thick, borders on and overlies the low-grade metamorphic Baxas and Dalings of the southern foothill belt towards the north, and separates them from the much more metamorphosed sedimentary zone of Central Bhutan. In western Central Bhutan this interior sedimentary metamorphic belt is again covered further to the north by very similar gneisses, which may actually be the continuation of those in the south. In eastern Central Bhutan this picture is changed by abnormal cross-striking elements and the introduction of fossiliferous non-metamorphic sediments. Here the southern gneissose belt is strongly reduced and covered by a thick sedimentary section completely different from the metamorphosed rocks of western Central Bhutan.

The Chasilakha gneisses, named after an attractive mountain village at 1950 m above sea level, cover a large tract of southwestern Bhutan west of the lower Mo-Chu or Sankosh River. They are most probably directly connected with the Darjeeling gneisses in the west. Along the Wong-Chu Valley the gneisses can be followed from south of Chasilakha for over 30 km to the south side of Chapcha (section B, Pl. II). Regionally the gneiss body forms a wide basin-like syncline, the outline of which is well visible in the relatively high mountains east of the Wong-Chu Valley. The detailed picture of this gneiss basin is more complicated. Actually two gneiss masses can be noted, a lower and southern one south of Chasilakha and a northern and higher mass to the north of it. They are separated by biotite schists, lenticular quartzites and conspicuously boudin-

aged garnet amphibolites. In the northern gneisses occur steeply north-east-dipping cross features with schists, thin quartzites, white marbles and lime-silicate bands. Both the southern and northern gneisses show a similar composition. They change from well-banded and layered, often lenticular and sheared gneisses (Ph. 60) into diffuse, migmatitic zones with intense sub-folding, marked by aplitic veins, which through increasing mobilization assume a more granitic aspect (Ph. 61). Orthoclase is dominant, the plagioclases are of intermediate composition. In the northern gneisses muscovite occurs with brown biotite, while the southern gneisses have mostly biotite, of a slightly more olive colour. The quartz forms irregular lobate grains intruding all other minerals and seems to be partly introduced through mobilization. Garnet is always present in varying quantity and forms a most characteristic constituent, emphasising the similarity with the Darjeeling gneisses. Fine-grained garnet-biotite granulites were observed in the northern gneisses.

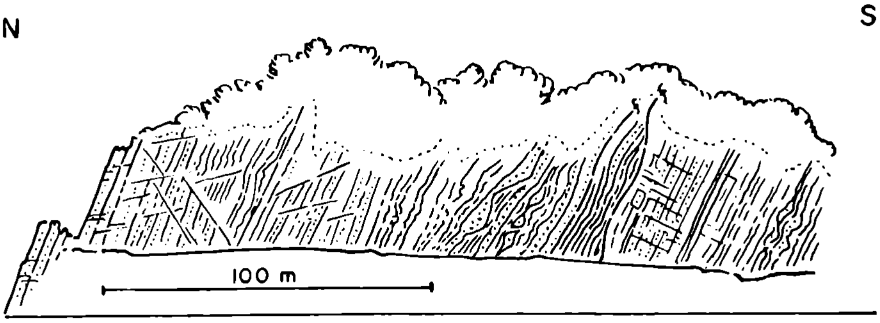


Fig. 127 *Fractured and boudinaged quartzites and sheard phyllites* between Hatisara and Suraya, SE Bhutan. Corresponds to nr. 5 in fig. 126; original by A. GANSSER

The two-mica garnet-bearing alkali-feldspar gneiss type is, as we have already noted in Sikkim, very widespread, and most characteristic for the large crystalline masses following above less metamorphosed sediments such as the already discussed Daling schists. East of the Sankosh River, the Chasilakha-type gneiss mass seems to be reduced by the eastern cross disturbances, and in the previously mentioned section north of Hatisara we noted only a small, complexly folded remnant (Fig. 126 and 128). These gneissose masses form the hills of Suraya and we call them Suraya gneisses. Southwards they are underlain by steeply northwards-dipping biotite schists. Similar schists, with boudinaged quartzitic lenses are intercalated and again overlie the gneisses towards the north. The main rock is a slightly migmatitic muscovite-biotite-granite gneiss with some garnets, not unlike the Chasilakha gneisses. Vaguely outlined aplitic and pegmatitic dykes are rather frequent (Ph. 62). Coarse muscovite-garnet-pegmatite to pegmatitic granites often include pockets of biotite-kyanite schists or intrude the schists in a most complex manner (Ph. 63). The overlying biotite schists are surprisingly rich in kyanites, either associated with vein quartz, or in pure aggregates of crystals up to 10 cm long. Further northwards the cover schists become

Fig. 128 *Shear zones in the granite gneiss of Suraya,* SE Bhutan (see also photo nr. 64); original by A. GANSSER

gradually less metamorphosed but are still highly stressed and sheared. The same shearing effect is visible in the Suraya gneisses, which are locally intensely folded and coupled with mylonitic shear zones (Ph. 64 and Fig. 128). In the Suraya region we witness again the extreme regional tectoni-

zation, indicating a south to southwest-directed steep thrust movement. These highly affected zones, characteristic along the southern Bhutan Lower Himalayas, contrast with the wider and gentler basin or monocline-type tectonic features following further to the north (sect. B and C, Pl. II).

Metamorphic sediments of the Paro belt

In western Bhutan the wide Chasilakha gneiss basin rises northwards and underneath appear highly metamorphosed sediments in which a certain argillaceous, calcareous and quartzitic sequence can be recognized. Granitic gneisses and some basic rocks are frequently intercalated. These metamorphics are well exposed along the valleys leading to the important centres of Paro in the Paro-Chu Valley and Timphu, the present capital, in the Wong-Chu Valley. The general structural configuration of these metamorphic sedimentary belts is indicated on the generalized section B and C on Pl. II. A regional north to northeasterly dip is visible in the Paro belt rocks, underlined by the conspicuous thick and well-bedded marbles and quartzites.

Two major zones of disturbance do occur, however; one in the lower Paro Valley striking east-west, and the other in the Wong-Chu above the confluence with the Paro-Chu, striking NNW. Both zones expose steep dips and are characterized by boudinaged amphibolitic lenses and associated garnet-bearing lime-silicate rocks with sheared biotite schists forming the main lubricant. Between the Wong-Chu disturbed zone and the confluence of the Wong-Chu with the Paro-Chu one observes a most conspicuous gentle granite gneiss dome, apparently a domal-folded thick laccolith consisting of laminated biotite-granite gneiss with diffuse migmatitic schlieren. Laterally, as well as below and above this gneiss body, follow garnet-staurolite-bearing muscovite-biotite schists, which constitute the main argillaceous rock type of the Paro metamorphics. Frequently the garnet schists are minutely folded and the garnets rotated. The fold axes dip southwards south of the dome and to the north on its northeast side (Ph. 65).

Most conspicuous in the Paro Valley are the banded marbles, called *Paro Marbles*. Three main marble zones can be distinguished in the Wong-Chu and Paro-Chu Valleys. The lowest horizon crops out just north of the Chasilakha gneiss basin in the Chapcha region. It is interbedded with garnet schists and frequently contains lime-silicate layers with boudinaged quartz veins (Ph. 66). The higher marbles occur in the Paro Valley proper, separated by quartzites, though a tectonic repetition may actually be possible. Here the marbles are banded with white and grey layers, ranging from a few centimetres to nearly one metre (Ph. 67). The banding is an original sedimentary feature marking more or less bituminous layers. The white bands are coarsely and the darker layers finely crystalline, in accordance with the well-known retarding effect of bitumen during recrystallization. Syngenetic folds are still visible in the banded marbles as well as primary pinch-outs of certain layers. Intercalated in the marbles are well-bedded mica schists and very coarse pure quartzites, with some small biotite flakes and large translucent quartz grains. Regionally, all the marbles and major quartzites show only gentle dips, mostly northwards or northeast-directed. Disturbances are, as already indicated, sharp linear features such as steeply dipping to vertical tectonized zones.

Above the upper Paro marble at Paro Dzong (Dzong = monastery fortress) follow schistose quartzites with characteristic large silvery muscovite flakes on the bedding planes. Locally single kyanite crystals are embedded. Northwards and upwards the meso-metamorphic quartzites show a gradual increase in metamorphic grade leading towards the next higher gneiss sheet.

In western Central Bhutan the Paro metamorphic belt is covered to the north, with a transitional contact in most sections, by a higher gneiss mass, the Takhtsang gneisses, which leads into the Higher Himalayan range. This fact is evident in the Paro-Chu, the Wong-Chu and the Mo-Chu Valleys, but eastwards of the latter conditions are different. The morphological and geological Higher Himalayas coincide no longer, and northern geological elements strike southeastwards along abnormal trends.

The sedimentary zones south and southwest of the Bumtang area

This sedimentary belt follows north of the Suraya gneisses which, as we have seen, most likely correspond to the Chasilakha gneisses of western Bhutan. It is more varied and considerably less metamorphosed than the Paro belt. Moreover it does not underlie the gneisses, but forms their northwards-dipping cover. This fact is evident on the enclosed generalized section of eastern Bhutan (sect. C, Pl. II).

The series starts with garnet-biotite schists, kyanite schists and garnet-sericite schists. Continuing northwards they become more phyllitic, and over garnet-bearing sericite schists one reaches a thick zone of phyllites (Sangsing-La). With the decrease of metamorphism the tectonization decreases somewhat from intense boudinage of the harder layers to folding with well-developed south-directed drag folds. These are well exposed in the steep valleys of the hill zone separating the

Suraya region from the large Tongsa-Chu Valley to the north. Thicker intercalations of grey-greenish fine-grained quartzites form more compact north-dipping layers with a strong and steep south-dipping fracture cleavage, while phyllitic intercalations show strong disharmonic folds, still with a rather consistent southwards vergence. Fold axes dip mostly gently towards the west (Fig. 129).

The regional metamorphism has now decreased to the phyllitic stage, but most of the sericitic phyllites show biotite porphyroblasts of rather late formation, not unlike the biotite in the Budhi schists of the Kumaon Himalayas above the crystalline sequence and at the base of the Cambrian sediments. Within conspicuously banded sediments with quartzites and greenish argillaceous layers of about 5 cm thickness the biotite porphyroblasts increase in the more argillaceous parts and become smaller and finally disappear in the more quartzitic horizons. This fact produces a somewhat reversed grading effect which clearly contrasts with normal cross bedding features well visible in the quartzitic layers (Ph. 68). In some instances the cross bedding is unmistakably clear and indicates that the sediments are in a normal position (Ph. 69). The certainty that we deal with a *normal sequence* is of particular importance, in view of the fact that further north and upwards the metamorphism increases again. The biotite porphyroblasts in the argillaceous bands are rotated only slightly or not at all, thus differing from the rotated porphyroblasts in sericite schists of the Budhi type. The latter type occurs frequently along the Tongsa-Chu Valley, where thick bodies of yellowish quartzites are intercalated. There is little doubt that the green argillaceous intercalations correspond to tuffaceous horizons. Some of these bands show a strong pressure cleavage, marked by the alignment of the biotite porphyroblasts (Ph. 70). These biotites are certainly late to post-genetic and cut some of the fine banding of the argillaceous horizons (Ph. 71).

Quartzites and biotite-psammite schists form a consistently northwards-dipping series free of the local disturbances met further south on both sides of Sangsing-La between the Suraya and Tongsa-Chu Valleys (Fig. 130). The yellowish weathered quartzites consist of translucent quartz grains with some small biotite flakes intercalated. The bulk of the Tongsa-Chu Valley rocks are, however, fine, dark-coloured biotite-psammite schists with more or less argillaceous bands. In the latter the biotite can increase, forming the typical biotite porphyroblast schists. Northwards, beyond Shamgong Dzong, the regional metamorphism increases slightly in the northwards dipping beds. Besides an increase in the biotite porphyroblasts some garnets appear. Zones of intense local sub-folding coincide with larger pegmatite and tourmaline granite dykes. Here a broad anticlinorium can be observed which seems to correspond to the large uplift of the so-called Black Mountain group (sect. C, Pl. II and Fig. 130). Further north and northwestwards the regional metamorphism decreases again, but the thick phyllitic horizons still contain more or less well-developed biotite, garnet and even chloritoid porphyroblasts (Ph. 72).

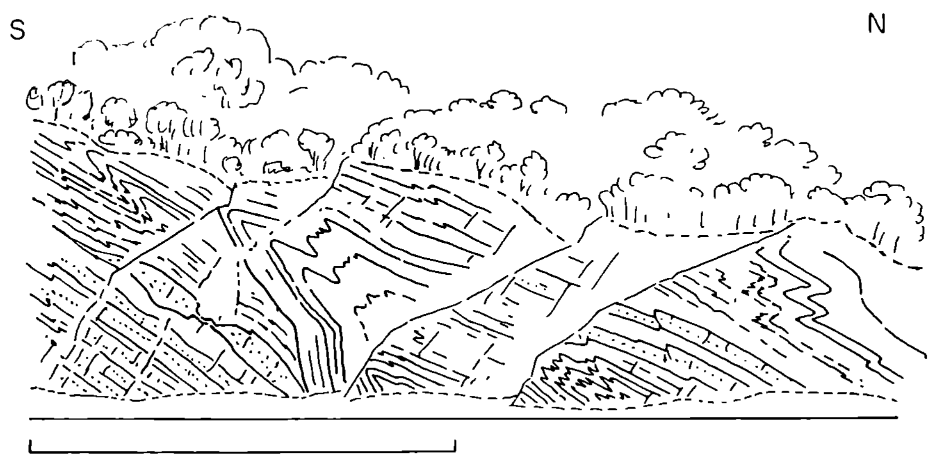


Fig. 129 *Disharmonic south-vergent folds and drag folds in quartzites and phyllites.* N of Sangsing-La, SE Bhutan; original by A. Gansser

Chendebi carbonate zone

Along the western branch of the Tongsa-Chu which leads to the Pele-La, an important pass in the core of Bhutan, follows a conspicuously

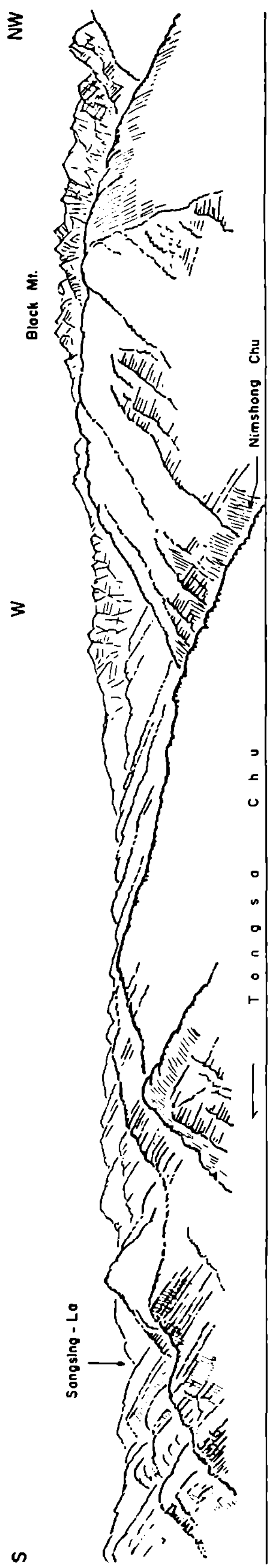


Fig. 130 *The regional north dip in the quartzites and psammitic schists* along the Tongsa-Chu Valley. To the right the culmination of the "Black Mountains"; original by A. GANSSER

Phot. 64 *Thrusts and shear zones in the highly disturbed migmatitic Suraya gneisses.* They reflect the strong tectonization of the Suraya crystalline along its steep thrust contact towards the schists in the south. The south side of the outcrop is at the right side of the picture. Suraya region, SE Bhutan (phot. A. Gansser)

Phot. 65 *Folded garnet schists* with thin quartzitic bands of the Paro metamorphic belt. The fold axes dip to the south. Middle Wong-Chu Valley. West Bhutan (phot. A. Gansser)

Phot. 66 *Lime-silicate zones* belonging to the lower Paro Marbles. Note boudinaged quartz veins within the flow textured lime-silicate. Chapcha. Wong Chu Valley, Bhutan (phot. A. Gansser)

Phot. 67 *Typically grey and white banded Paro Marbles.* The less bituminous layers are coarser crystalline. Primary sedimentary features are still preserved. (Lensing, slightly cross-bedding, pinch-outs.) Paro, W. Bhutan (phot. A. Gansser)

Phot. 68 *Banded quartzites and green shales,* the latter with post genetic biotite porphyroblasts, increasing towards the more argillaceous part and producing a reversed grading effect, contrasting with the normal cross-bedding (cut out) visible at the upper right side of the picture. Syngenetic sedimentary features are well preserved. North Sangsing-La. SE Bhutan (phot. A. Gansser)

Phot. 69 *Alternation of thick and cross-bedded quartzites with green tuff horizons,* characterized by biotite porphyroblasts (t). North Sangsing-La, SE Bhutan (phot. A. Gansser)

Phot. 70 *Pressure cleavage in green tuff horizons between quartzites.* The cleavage surfaces are marked by a conspicuous growth of biotite porphyroblasts. (Detail of outcrop Ph. 69, just left of lower band.) North Sangsing-La, SE Bhutan (phot. A. Gansser)

Phot. 71 *Syngenetic small slump-folds with superimposed post-genetic biotite porphyroblasts along the argillaceous bands.* Sedimentary section north Sangsing-La, SE Bhutan (phot. A. Gansser)

Phot. 72 *Chloritoid-bearing biotite-garnet schist. N of Nada-La, (Bhutan).* The garnets are rotated with quartz in the stress shadows. 1 garnet, with lobate edges, 2 quartz, 3 sericite, concentrated on stress front, 4 quartz, feldspars biotite and chloritoid. Enl. 15×

Phot. 73 *Sillimanite-garnet-biotite gneiss. Takhtsang Monastery, (NW Bhutan).* 1 garnet rich in quartz inclusions, 2 sillimanite, 3 biotite, quartz and feldspars. Enl. 15×

Phot. 74 *Rotated garnets in biotite-muscovite-psammite gneiss. Bumtang,* (E Bhutan). Enl. 45×

Phot. 75 *The Takhtsang Monastery,* the type locality for the Takhtsang gneisses, the eastern representative of the Darjeeling gneisses. The thick-bedded sillimanite-bearing garnet-biotite gneisses dip gently to the north. The rock wall faces the southwest. Takhtsang, Upper Paro Valley, W Bhutan (phot. A. Gansser)

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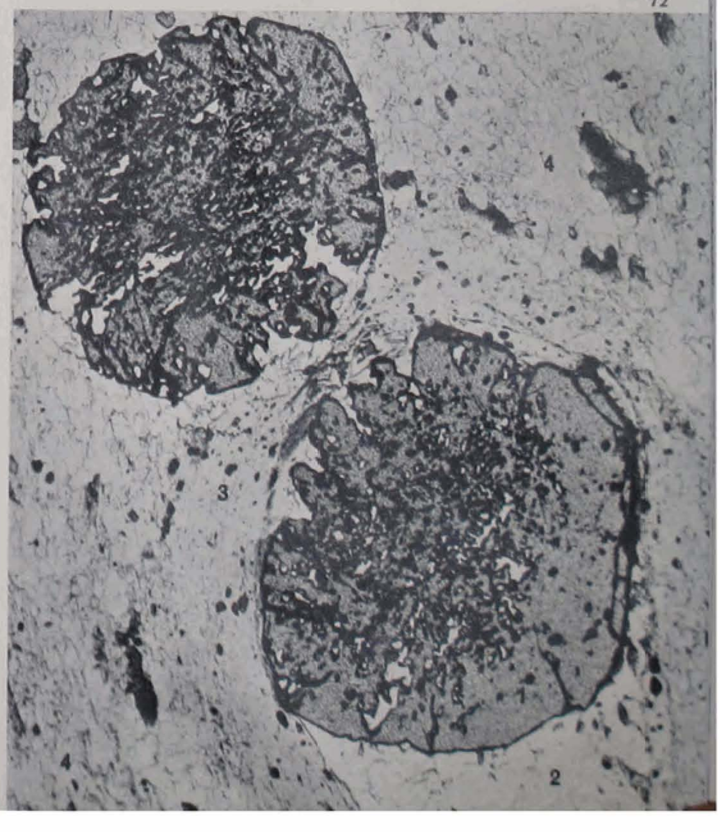

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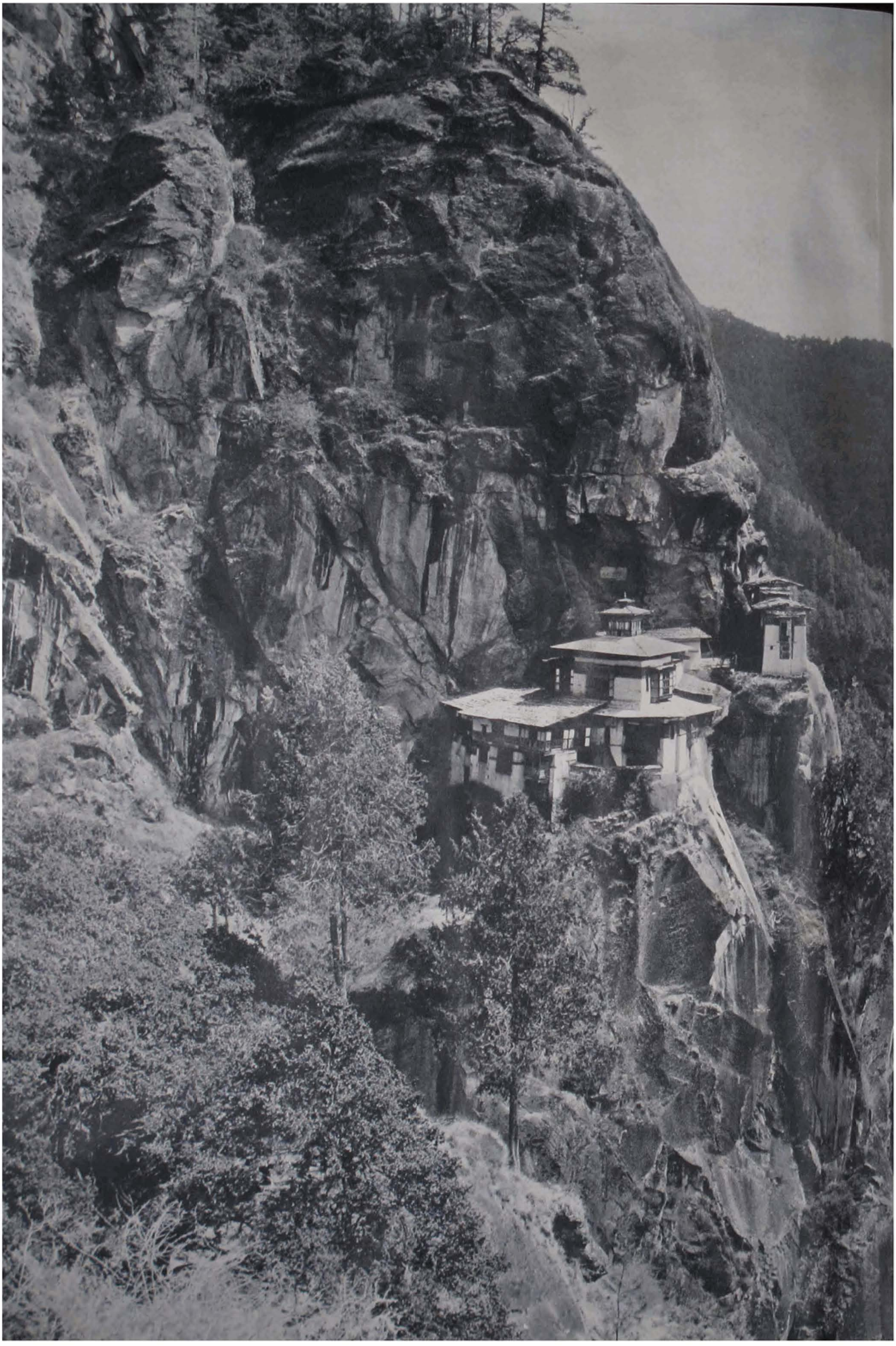

steeply northeastwards-dipping zone of carbonate rocks, in which fine-grained *white sugary dolomites* form horizons up to 300 m thick. They alternate with finely banded white and yellow marbles, whose banding is partly accentuated by thin dolomitic seams. Intercalated are biotite and garnet phyllites. The carbonates are well exposed at the small village of Chendebi, and we thus call them the *Chendebi carbonate zone*. Apart from the typical lithology, the steep-dipping Chendebi zone forms a pronounced tectonic trend from NW towards SE. Northwest of Chendebi a fault zone with highly disturbed and conspicuously black graphitic phyllites cuts off the carbonate rocks towards the west.

Tang-Chu Series

Westwards, over the Pele-La, we note again garnet-bearing sericite-biotite schists with intrusions of tourmaline granite and pegmatites. This zone continues into the local basin of the Tang-Chu west of Pele-La where non-metamorphic sediments are of particular interest, having furnished some lower Palaeozoic faunas. The Pele-La schists become slaty, the biotite and garnets disappear as well as the local intrusions and along the Tang-Chu only black slates, dark grey calcareous siltstones and irregular limestones are met. They strike towards the NNE and the gently dipping beds form a flat syncline and anticline. This important sedimentary sequence has been called the *Tang-Chu series*. They have furnished badly preserved, but still partly determinable fossils. The only samples with determinable fossils were found in the river, but there is no doubt that the material is derived from the nearby outcrops which are lithologicaly identical. Fine-grained silty limestones contain small gastropods and thin shell fragments. Of particular interest are dark grey finely crystalline limestones with corals, which are unfortunately not well preserved. No specific determinations of the corals were possible, but the following forms seem to be present:

1. Probable old Palaeozoic *Rugosa* (no genus or species determinable).
2. Thamnoporidae, presumably *Thamnopora* or *Pachypora*.
3. *Stromatopora*, presumably *Actinostroma*.

This horizon most probably represents the Devonian (or Silurian).

I am greatly indebted to H. Flügel (Graz) for having made a quick preliminary determination, allowing me to include the results in the present text. The presence of marine Devonian (Silurian) sediments in the very centre of Bhutan is of great general interest, and certainly deserves additional work in this region.

The northwards extension of the Tang-Chu sediments is not known. The valley is not large and ends in the mountains of the western upper Tongsa-Chu or Mangde-Chu, where we observed a northeastwards-dipping trend of the gneisses and highly crystalline carbonate rocks which have no affinities with the Tang-Chu formation. To the west the Tang-Chu beds are underlain by calc-schists and further west by green slates not unlike the Dalings. Towards the important place of Wangdiphodang in the Mo-Chu Valley granite gneisses, migmatitic gneisses and some lime-silicate bands occur, leading towards the large crystalline mass of northwestern Bhutan. Southwards the Tang-Chu beds seem to rise and to be again underlain by metamorphic rocks. It is thus most likely that the Tang-Chu region forms a local sub-folded basin where these peculiar sediments have been preserved. They seem unrelated to the sediments of the northern Himalayas, and together with the Pulchauki Ordovician beds of Central Nepal (p. 148) are so far the only fossiliferous horizons in this central belt of the eastern Himalayas.

BHUTAN HIGHER HIMALAYAS

The boundary of the Higher Himalayas of Bhutan is arbitrarily placed at the beginning of the main crystalline masses north of the more or less metamorphosed sedimentary zone of Central Bhutan. The division is not such a clear morphological separation as in other areas of the Himalayas. Here the higher mountains mostly coincide with the border range towards Tibet. At the base of the crystalline sheet we miss, however, the marked change in metamorphism clearly displayed along the Main Central Thrust of the Central Himalayas, and as we have already noted in Sikkim, it is anybody's guess where to place a thrust boundary. A certain change from meso- to kata-metamorphic grade can be recognized in some sections (western Bhutan) and it is here that we have placed our main tectonic division. Indications of tectonic disturbances do exist, but their magnitude remains doubtful. A further fact supporting the separation of the Higher from the Lower Himalayas is the mostly normal sedimentary cover with upwards decreasing metamorphism following above the crystalline masses of the Higher Himalayas. Most of the crystalline sheets in the Lower Himalayas have a reversed metamorphism. These conditions are only partly applicable to the Bhutan Higher Himalayas.

Takhtsang Gneiss

North of Paro in northwestern Bhutan, the Paro metamorphics are covered along a more or less transitional contact by a large and extensive

gneiss mass. Clinging to a near-vertical cliff of these gneisses is the famous *Takhtsang Monastery* (Ph. 75) which has been taken as the type locality for the Takhtsang gneisses. The contact between the Paro marbles and quartzites with the Takhtsang crystalline is shown in Fig. 131. Along this section we note a change from the epi- to meso-metamorphic Paro marbles and quartzites to the sillimanite-bearing gneisses. We assume the major Takhtsang gneisses and Darjeeling than with the Chasilakha gneisses further to the south, which seem to form a direct continuation with the Darjeeling gneiss of Sikkim.

Northwards, following the Paro-Chu, well-bedded quartzite horizons, mostly coarse-grained and with translucent quartz grains, occur intercalated in the northwards-dipping Takhtsang gneisses. Some more schistose zones, consisting

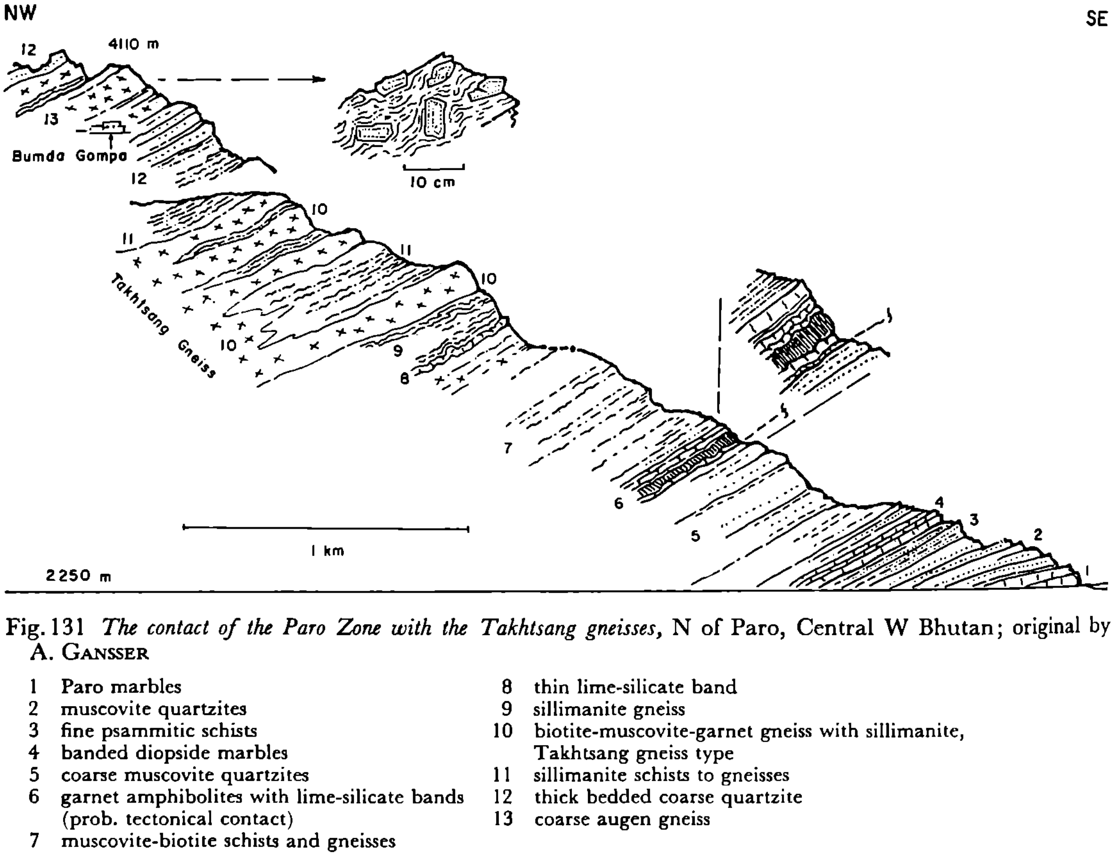

Fig. 131 *The contact of the Paro Zone with the Takhtsang gneisses*, N of Paro, Central W Bhutan; original by A. Gansser

1 Paro marbles
2 muscovite quartzites
3 fine psammitic schists
4 banded diopside marbles
5 coarse muscovite quartzites
6 garnet amphibolites with lime-silicate bands (prob. tectonical contact)
7 muscovite-biotite schists and gneisses
8 thin lime-silicate band
9 sillimanite gneiss
10 biotite-muscovite-garnet gneiss with sillimanite, Takhtsang gneiss type
11 sillimanite schists to gneisses
12 thick bedded coarse quartzite
13 coarse augen gneiss

tectonic contact along conspicuous garnet amphibolite zones showing boudinage and marked zones of movement.

The Takhtsang rocks at the type locality consist of banded sillimanite-bearing garnet-biotite gneisses with white quartz and aplite seams (Ph. 73). Locally the banding can become diffuse and the more massive gneisses appear to have been mobilized. There are all gradations to migmatitic types, with most of the original mineral content preserved. Within the gneisses occur eye-shaped lenses of fine-grained lime-silicates, rich in garnet, diopsidic augite, labradorite feldspar but devoid of micas. The whole aspect of the Takhtsang gneisses with its inclusions is strikingly similar to the Darjeeling gneisses; actually the similarity is even better between the of biotite-garnet schists are also seen within the gneisses. As a whole the characteristic gneisses are widespread all along this northern belt of Bhutan. They were met again in the Wong-Chu above Timphu, and form near-continuous outcrops along the Mo-Chu where, interrupted only by the marble zone of Tamji, they extend northwards to the Tibetan border, culminating in the impressive Masa Kang Mountain group (Ph. 83). The gneisses along the Mo-Chu differ, however, from the type of Takhtsang by their less uniform composition, which is caused by granitization, by frequent migmatitic zones and often prolific dyke intrusions connected with the regional young tourmaline granite intrusions along the Tibetan border. The lenticular lime-silicate concretions are less frequent, and in their place occur thin

bands of marbles or lime-silicates. The structural aspect of the Mo-Chu gneisses is shown on the enclosed section C, Pl. II.

In eastern central Bhutan Takhtsang-type gneisses are widespread in the Bumtang area. They rise east and northeast of the Chendebi carbonate zone and north of the phyllitic rocks already described from the middle Tongsa-Chu. Their southern border is formed by often intricately folded muscovite-biotite-garnet schists, intruded by muscovite pegmatites and more rarely by biotite pegmatites and aplitic tourmaline granite dykes. The dyke system is definitely younger than the gneisses, since the latter are cut by similar dykes (see also absolute age determinations in last general chapter). The gneisses are well exposed in the gorge leading to the famous Tongsa Dzong, the birthplace of united Bhutan. For this eastern part of Bhutan we will introduce the local name of *Tongsa gneisses*, though we associate them with the Takhtsang gneisses of western Bhutan, with which they have many features in common. The Tongsa gneisses are characteristically banded and striated (Streiffengneis) and some of the bands expose minute but intense southwards-directed flow folding. They consist of muscovite-biotite-granite gneisses and differ by the larger amount of muscovite and the scarcity of garnets from the otherwise similar Takhtsang gneisses. Migmatitic zones and locally fully granitized and mobilized sections are often met.

The Bumtang region ENE of Tongsa forms a wide flat anticlinorium with biotite-psammite gneisses, stressed garnet schists (Ph. 74) and thin lime-silicate bands in the core. Northwards, the Tongsa-type banded gneisses set in again dipping north and can be followed until a conspicuous intercalation of steep-dipping marble zones which separates a more northern granite gneiss zone, where younger granites and their related dyke system are particularly widespread.

The culmination of the Bhutan Higher Himalayas forming the border towards Tibet has been studied by the author in three different regions, each displaying geological features quite different from the others. They are therefore described under three different headings, each representing the dominant mountain peak of the respective area, viz.:

the Chomolhari region,
the Masa Kang region, and the
Gankerpünzum region, the latter named after the highest peak in Bhutan.

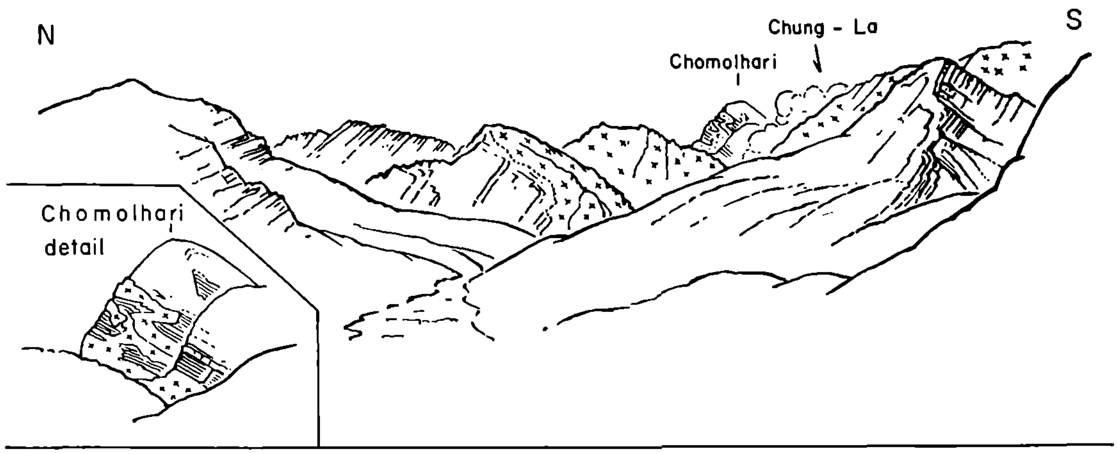

Fig. 132 *The Chung-La Valley towards Chomolhari,* NW Buthan, original by A. Gansser
calc schists and phyllites intruded by the Chomolhari granites

Chomolhari region

In the upper Paro-Chu the Takhtsang gneisses are intruded by *tourmaline granites*. They interfinger sill-like with the well-bedded gneisses and increase from the south to the north. They form a large body crossed by the Chung-La southwest of Chomolhari (Fig. 132). Since the same granites form substantial sills in the well-known Chomolhari Mountain, we call them *Chomolhari granite*.

Westwards, towards the Peme-La (Tremo-La) and the Phari basin, which we know already from the Sikkim area (p. 182), the Chomolhari granites are intrusive into the phyllites and calc-schists forming the base of the sediments of Phari. They dip regionally to the west, into the Phari depression. Phyllites with the characteristic biotite porphyroblasts form the oldest outcrops with intercalations of calc-schists and marbles

which, like the sedimentary cover of Everest, could be compared to the pre-Triassic Khongbu series of HAYDEN (1907) in the Phari basin.

Towards the northeast, after crossing the bulk of the Chomolhari granite, we enter rather unexpectedly into a wide basin of unmetamorphic sedimentary rocks, outcropping in a wild array of peaks and valleys south of the main Chomolhari Range (Ph. 76 and 77).

to the south, closing the basin in this direction. A tentative cross section is enclosed in order to outline the structural aspect of the wider Lingshi basin (Fig. 133). The northern contact against the Chomolhari Range is not only intrusive, but down-faulting marks the rapid change from the marbles, lime-silicate and granite sills to the unmetamorphic Mesozoic sediments.

The base of the Lingshi sedimentary sequence

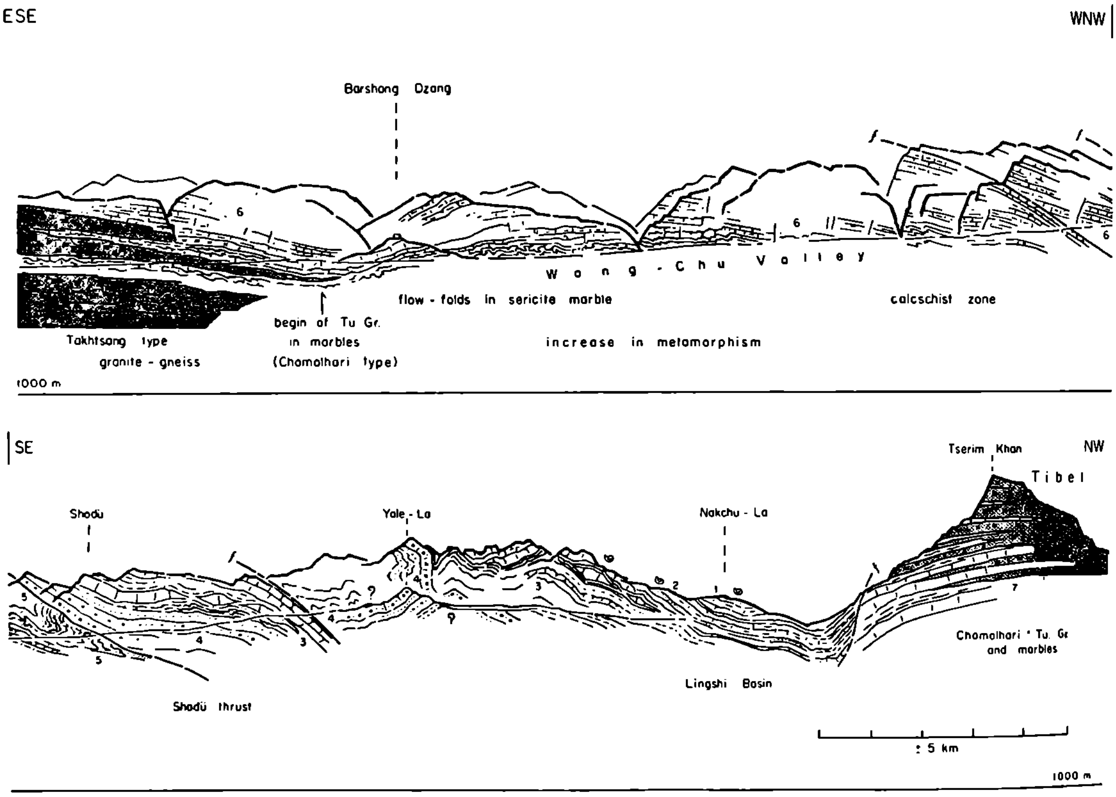

Fig. 133 *Section across the Lingshi and Wong-Chu Valley,* NW Bhutan; original by A. GANSSER

1 Cretaceous Jurassic shales and silts with ammonites
2 black slates with ammonites, Trias
3 limestone lenses and crinoidal calc-schists, Permo Carboniferous?
4 quartz conglomerate and calc-breccias, some tillitic (Carboniferous?)
5 cherty quartzites and red shales, highly folded
6 marmorized calc-schists and marbles, often with flow structures
7 young tourmaline granite, Chomolhari type
8 migmatitic gneisses, Takhtsang type

Lingshi Basin

The youngest sediments occur in the Lingshi Dzong region, and therefore we call the whole region the *Lingshi basin.* To the west and north the Lingshi basin is limited by the intrusive Chomolhari granite. South and southwestwards it extends far down the Wong-Chu River where the lower calc-schists and marbles form spectacular gorges. Here the southern limit is again intrusive, with sills of Chomolhari-type granite, but otherwise the deeper Takhtsang gneisses rise

exhibits carbonaceous rocks altered to marbles, lime-silicate rocks and highly crystalline calc-schists. They are well exposed in the deep gorges of the Wong-Chu where the deeper horizons show intense flow folding. On this very preliminary survey we could only guess the real thickness of the carbonate rocks since repetition by steep thrusting seems to double the section. Normal profiles of over 1000 m are certainly present, with a remarkably constant development of the banded and slaty calc-schists and marbles. The argillaceous content is relatively low, and quartz-

ites seem to be missing altogether along this lowest horizon. Most likely, the banded marbles and lime-silicate rocks observed alternating with the tourmaline granites in the Chomolhari Range are an equivalent of these lowest carbonate rocks which seem to be thinning to the north and show a remarkable increase in mostly thermal metamorphism.

Towards the Yale-La the calc-schists are overlain by thin-bedded quartzites and shales, striking by their intense disharmonic folding. This coincides with a major thrust pushing the next sequence of greywackes over the carbonates. The tectonic contact is well exposed near the small community of Shodü in the upper Wong-Chu. *The greywacke formation* begins here with a pebbly horizon notable for the sparce, unsorted and irregularly distributed sub-rounded pebbles of quartzites set in a dark greenish grey, silty, unsorted matrix. The whole aspect is not unlike certain Blaini tillites and, based on present knowledge, one might suggest a similar origin and age for the base of this greywacke formation. It certainly is in striking contrast with the underlying carbonate rocks and, as we will see, with the younger limestones and shales.

On Yale-La we find again conglomerate horizons differing somewhat from the lower greywacke types by the content of subangular black siliceous limestones and quartzitic siltstones. Intercalated are black phyllites and brown quartzites. The higher beds are rendered conspicuous by their thick irregular limestones often tectonically transformed into giant boudins. These are interbedded with grey and red calc-schists. Some of the limestones are dense and are covered with thin very irregularly displayed argillaceous films. Greywackes and dark grey phyllites are still present between the limestones, but decrease in importance from south to north. Upwards calc-schists and more regularly bedded limestones contain some crinoids. H. Hess (Binningen) kindly looked at some of the material, but the bad state of preservation only allowed the suggestion that the crinoids are possibly Palaeozoic forms of the *Camerata* type.

The calcareous sequence is followed by more argillaceous horizons, still alternating with limestones. In one of the black, slightly micaceous slates my assistant, R. Hänny, discovered the well-preserved negative of an ammonite which we considered to be a Norian *Parajuvavites*, an assignment later confirmed by B. Ziegler.

The higher beds are mostly well-bedded to platy silty shales and marls with fine calcareous siltstones, most of it with olive-grey weathering and originally dark-grey to black. They form rounded hills subject to an extensive solifluction which masks the primary contacts of the various horizons. Some fine sandy to silty micaceous horizons contain lamellibranchs resembling *Pseudomontis* and *Carditas*, without allowing generic determinations. They may represent Jurassic horizons, since the higher silts and shales already include faunas of Cretaceous affinities. Northeast of Lingshi Dzong layers of fossiliferous black spathic limestones occur in black shales. They contain several lamellibranchs such as *Trigonias*, and ammonites, of which the Hoplitaceae and Hoplitidae suggest an Albian age. Another Cretaceous fauna was found in the platy siltstones of the Nakchu-La, with ammonites representing probably *Probysteroceras (Goodhallites?)* and other small compressed forms, possibly *Mortoniceras* or *Hyseroceras* also of Albian age. I am greatly indebted to R. Trümpy (Zürich), and B. Ziegler (Zürich), for the investigation and determination of this fossiliferous material.

The presence of Middle Cretaceous in the shales of the Lingshi basin, for which I propose the name of *Lingshi formation*, is of great interest. They seem to represent a facies different from the Tibetan Kampa system and to be more in line with the widespread, somewhat Flysch-like Jurassic of southern Tibet. The Lingshi basin is certainly an area where detailed studies are warrented. No younger rocks were noted during our rapid traverses. It is not known if a direct connection of the Lingshi basin with the sediments of the Phari-Tuna region does exist. This could only be possible in the depression between the Chomolhari Range and the high mountains of the Masa Kang region in the northeast.

Chomolhari Range

We have already noted that the Lingshi basin is bordered towards the north and northwest by the impressive range of the Chomolhari group. The rather abrupt change of the Cretaceous Lingshi shales against the granites and marbles of the south face of the Chomolhari Range has been accentuated by a normal fault zone (Fig. 133). The base of the Chomolhari consists of thick-bedded marbles, which increase from the southwest to the northeast and can reach a thickness of 1000 m, topped by thinner-bedded marbles. Within the latter, and partly also in the lower marbles, are intercalations of biotite schists and banded greenish quartzites. Sills of white tourmaline granite (our Chomolhari granites) intrude into the schists, marbles and calc-schists. They increase towards the west and northwest as well as upwards, and form larger granitic masses. At the base of the main Chomolhari peak (Ph. 78) occur wildly folded migmatites, fully embedded in a homogenous mass of tourmaline granite. The relation of these migmatites with the sedimentary sequence is not yet known.

Of special interest are the widespread granite sills and their relation to the surrounding car-

bonate rocks. The sills are remarkable for their strikingly constant development in composition and size. Irrespective of their thickness, which may vary from a fraction of a metre to over 100 metres, they may extend for several kilometres. This poses the important problem of their *mis en place*. Most of the sills do not occur within crystalline rocks, from which they could have been formed by "lateral segregation" with none or only a short travel of the new granitic material. They are emplaced in carbonate rocks which have been altered to marbles or, if impure, to complex lime-silicate marbles. The larger part of the precipitous south walls of the Chomolhari Range consists of such a repetition of marbles and granite sills, wonderfully displayed in some of the spectacular cliffs (Ph. 79). The contact of the granite sills, regionally concordant to the sedimentary bedding, can in detail be rather wavy, following the slight increases and decreases in the size of the sill. These changes are not reflected by the sediments, which are very sharply cut by the granite. In many places the marbles and lime-silicate rocks expose flowing features, and thin quartz bands are often involved in complicated flow folds and boudinage (Ph. 80 and 81). All flow features are sharply cut by the granites. In spite of this, real crosscutting dykes are rare. One major exception can be seen on the western face of Chomolhari, where a very large folded dyke of granite cuts through the bedded sediments (Fig. 132).

The composition of the granite is strikingly similar to the already mentioned Badrinath tourmaline granites of Kumaon. They contain some larger orthoclases with acid plagioclases, mostly as oligoclase, and lobate irregular-shaped quartzes together with biotite and/or muscovite, and always a black tourmaline. The feldspars and quartzes dominate over the micas, which results in the pronounced white colour of the fresh granites.

The composition and shape of the granites and their relation to the surrounding carbonate rocks clearly indicate the *intrusive character* of the granites. We have here an excellent example of the way in which thin (often less than one metre thick) acid granites have intruded as sills for several kilometres. The surrounding rocks leave no other alternatives. The contact minerals of the limestones, mostly diopsidic augites and cordierite with a large amount of sphene, give some indication of the temperature involved. No difference can be observed in the composition and shape of the granite sills whether they are intrusive into biotite schists, quartzites or limestones, though the latter rocks are dominant. We can only draw attention to this problem, which invites future detailed investigations.

The granite decreases in amount in a northeastern direction. In the more eastern peaks of the Chomolhari Range, the limestones have considerably increased, and the granites become restricted to the higher horizons. This is well visible in the beautiful Tserim-Kang peak which already displays a thick foundation of limestones (Ph. 82). The largest body of Chomolhari-type tourmaline granites, as we will see later, outcrops in northeastern Bhutan, in the Gankerpünzum region. In between, in the mountains of the Masa Kang group, only migmatites and small irregular dykes indicate a certain mobilization. The fantastic sill intrusions of the Chomolhari are not found in the more eastern areas.

Masa Kang region

While discussing the Takhtsang gneisses we noted that they extend along the Mo-Chu Valley northwards into the Masa Kang region near the Tibetan border. Our section B, Pl. II runs along this same line. We see on this section how the Takhtsang-type gneisses form a wide basin plunging eastwards, divided by the conspicuous marble zone of Tamji, which is not unlike some of the Paro marble zone except that the marbles are coarser, mostly white and rich in lime-silicate zones. A frequent granitization in this part of the gneisses may be the reason for the higher metamorphism of the marbles.

Following a short but accentuated steeply northwards-dipping tectonic zone which strikes ESE and passes south of the remote little village of Laya, we reach the culmination of the Masa Kang mountain group. A broad anticline coincides with the Masa Kang summit, the axis striking WNW and plunging in this direction towards the Tibetan border. The basal rock type is still a biotite-(muscovite)-garnet gneiss, often with sillimanite-rich zones. In the Masa Kang region these gneisses have, however, been strongly mobilized and locally granitized, as witnessed by a prolific system of dyke intrusions and widespread migmatites (Ph. 85). Most of the dykes seem to have some relation with the Chomolhari granite intrusion, but nowhere in this area do tourmaline granites form any substantial mass. This fact contrasts strongly with the Chomolhari and the more eastern region (Gankerpünzum) to be discussed in the next section.

On the south side of the Masa Kang dome occur boudinaged garnet amphibolites together with some lime-silicate layers. They indicate a tectonic division between the gneissic horizons. The garnet amphibolites are of special interest, with garnets forming sieve-like inclusions in large hornblende crystals, and each garnet is surrounded by a white rim of andesine labradorite which seems to have partly replaced the originally larger garnet porphyroblast (Ph. 84). Within the more migmatitic gneisses occur fully mobilized

medium to fine-grained granites, which begin to intrude discordantly into the otherwise rather diffuse migmatites. Such locally developed granitic zones are frequent in the otherwise highly migmatized main body of the Masa Kang peak (Ph. 83). Under the microscope, the patchy granites of Masa Kang are seen to consist of larger orthoclases, some with a myrmekitic border, and strongly zonar plagioclases, with a border of oligoclase and a core of basic andesine. Quartz is most irregular and often occurs as inclusions in the feldspars or borders them irregularly; it looks as if it were partly introduced. Biotite is generally common, together with some muscovite, but tourmalines are missing. The biotite and muscovite are often intergrown within the same crystal flake. In other granites only biotite is present. The zonar plagioclases, the quartz infiltration, and the lack of tourmaline distinguish these granites from the youngest tourmaline granite types.

A prolific dyke system varying from pegmatites, tourmaline granites to tourmaline aplites crosses the more or less migmatized gneisses. Many of the coarser dykes have a fine aplitic border zone, which sometimes seems to branch into the aplitic sill-like bands intercalated in the already migmatitic gneisses (Ph. 86). Some of the dykes clearly follow pre-existing fault zones within the well banded, often psammitic gneisses, where the rather sharply defined psammitic bands indicate the amount of displacement (Ph. 87). One can also note how fine-grained aplite-granites finger out into highly migmatitic but still banded gneisses (Ph. 88).

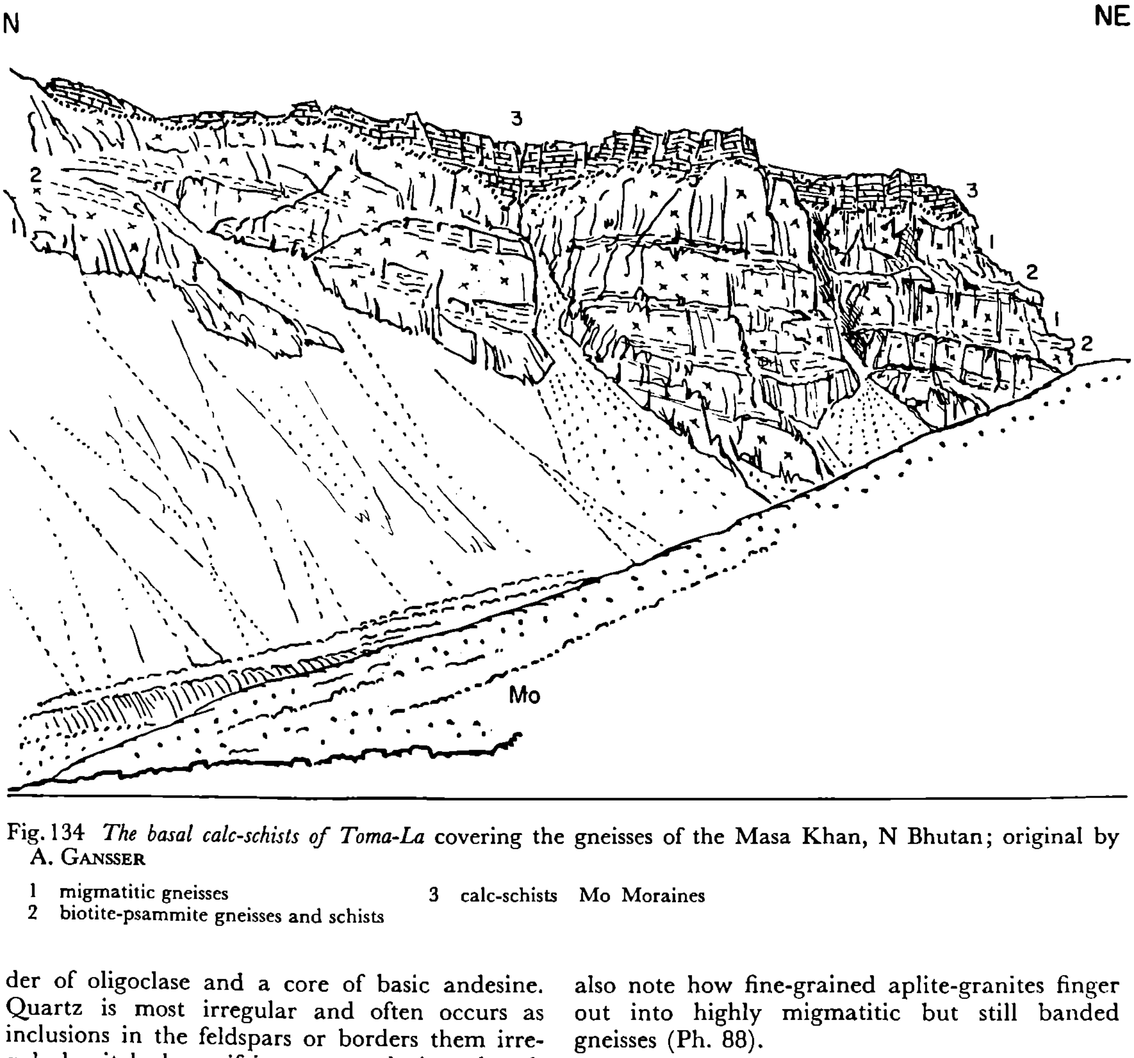

Fig. 134 *The basal calc-schists of Toma-La* covering the gneisses of the Masa Khan, N Bhutan; original by A. Gansser

1 migmatitic gneisses
2 biotite-psammite gneisses and schists
3 calc-schists
Mo Moraines

Sediments of Toma-La

Towards the Tibetan border north of Masa Kang the migmatization of the gneisses decreases but young aplitic granite dykes and somewhat older sills are still present and contrast here more strongly with the often psammitic biotite gneisses. The granite dykes clearly cut the aplitic sills (Ph. 89). The gneisses as a whole still dip rather gently northwards and are then followed near

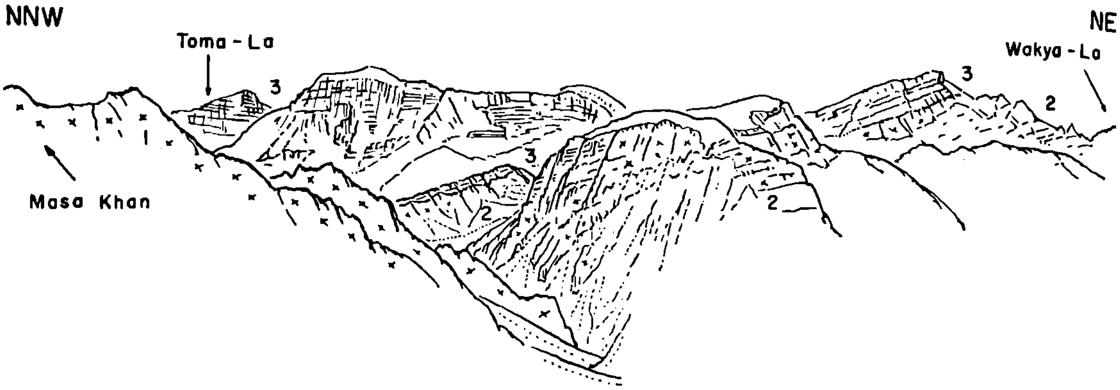

Fig. 135 *The Toma-La sedimentary cover on Masa Khan gneisses,* N Bhutan; original by A. GANSSER

1 granite and granite gneisses of Masa Khan
2 psammite gneisses and migmatitic gneisses
3 Toma-La calc-schists and limestones

the Tibetan border by calc-schists above a sharp discordant transgression (Fig. 134). These calc-schists form the base of a thick sedimentary series which was observed only in the higher peaks to the east of Toma-La (Fig. 135). They are not unlike the transgressive carbonate rocks south of Lachi (N. Sikkim), described by WAGER and correlated with the Everest limestones. Their regional dip seems to be northwards-directed and the calc-schists may form the base of the widespread Jurassic sediments south of the Tsangpo River in southern Tibet. The calc-schists cover the irregular gneiss surface with a sharp contact and it is quite surprising that, as far as could be seen, no dykes seem to enter the carbonate schists (Fig. 134). The basal calc-schists contain a wild mixture of larger diopside crystals, cordierite grains, bands of biotite and mid-basic plagioclases in a groundmass of irregular calcite grains, most of them conspicuously twisted and bent. It appears that the calc-schist contains reworked material of lime-silicate rocks and is itself apparently again metamorphosed, as indicated by the biotite bands. Strangely enough, real migmatitic relics from the underlying crystalline rocks seem to be missing, and the relation of the calc-schists with the gneisses is still somewhat obscure.

The basal calc-schists are overlain by yellowish marmorized limestone bands and eventually calc-schists, not unlike the yellow bands of the Everest carbonate series. Still higher limestones were found only as boulders in the moraines coming from the glaciers north of Masa Kang. They bring down boulders of white crinoidal limestones, light-grey limestones with probable Fusulinids, platy grey silty limestones with shell fragments, coarser limestones with traces of corals and blocks of dark-grey limestones with large cross sections of megalodontid shells. So far these samples have not been investigated palaeontologically, but, based on the field evidence, they may represent a predominantly calcareous sequence from Permo-

Phot. 76 *The wild peaks formed by the synclinally arranged sediments of the Lingshi basin,* to the south of the Chomolhari Range. The upper well-bedded horizons belong already to the Mesozoic carbonate and shale formations. NW Bhutan (phot. A. Gansser)

Phot. 77 *The well-bedded Mesozoic sediments of the Lingshi basin* forming wild peaks south of the Chomolhari Range. The westwards rising Lingshi syncline passes between the two unnamed peaks. NW Bhutan (phot. A. Gansser)

Phot. 78 *The south face of Chomolhari main peak* (7315 m) with well-bedded marbles, schists, quartzites and migmatites intruded by sills of tourmaline granite. Foreground old castle of unknown origin. NW Bhutan (phot. A. Gansser)

Phot. 79 *The precipitous south wall of the eastern Chomolhari Range.* Well-exposed marble bands intruded by surprisingly constant sills of white tourmaline granite. Excellent example of acid granitic sheet intrusion into carbonate rocks. The summit ridge forms the Tibetan border. NW Bhutan (phot. A. Gansser)

Phot. 80 *Flow folds in lime-silicate marbles* with stretched, folded and rolled quartz veins. The sill of young tourmaline granite (upper part of picture) borders the carbonates with a sharp but not always strictly parallel contact. Southern slopes of Chomolhari Range. Changmutang Valley. NW Bhutan (phot. A. Gansser)

Phot. 81 *Thick sills of tourmaline granite cutting through banded lime-silicate marbles* with boudinaged quartzite inclusions. On the right hand side a granite dyke cuts through the banded marbles, connecting with a higher granite sill.

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Carboniferous to at least Triassic. They have been derived from the higher peaks along the Tibetan border (Fig. 135).

Djüle-La zone

This steep carbonate zone has a consistent strike from northwest to southeast. It is first met in

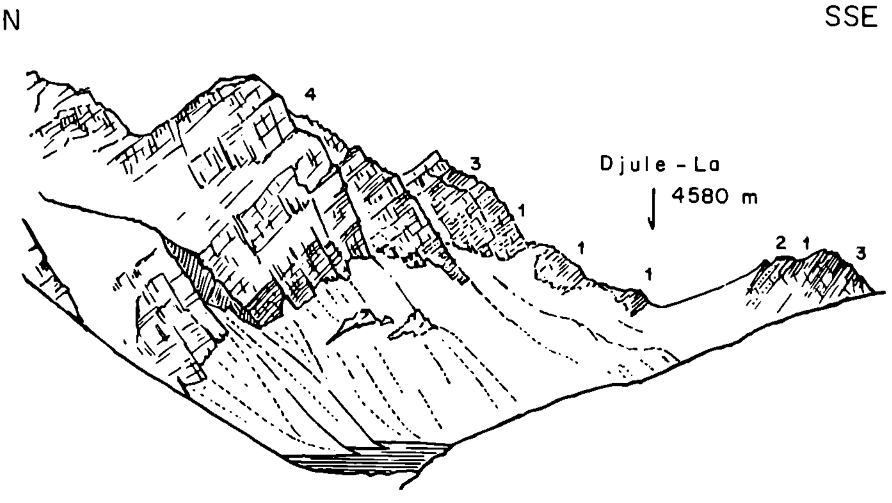


Fig. 136 *The steeply north-dipping Djüle-La zone,* between Bumtang and Gangerpünzum, North Bhutan; original by A. GANSSER

1 garnet-biotite schists
2 banded quartzites
3 banded marbles and calc-schists
4 thick bedded dolomite and limestone marbles

Gankerpünzum area

In eastern central Bhutan, the Tongsa gneisses, the eastern equivalent of the Takhtsang gneisses, form a wide anticlinorium in the Bumtang area and can be followed northwards to where they steepen abruptly and are succeeded by a conspicuous steep zone of schists, quartzites and carbonate rocks which crosses the Djüle-La (Sect. C, Pl. II).

the lower Chanka-Chu (upper Bumtang-Chu) in the southeast and crosses the Djüle-La into the Mangde-Chu Valley or upper Tongsa Valley, continuing from there further to the northwest into geologically unknown territory. The name is derived from the Djüle-La (Pass) with its excellent exposures. In the lower Chanka-Chu the Tongsa-type gneisses are covered by staurolite-kyanite and garnet schists alternating with coarse marbles. Locally sills of a coarse, pegmatitic

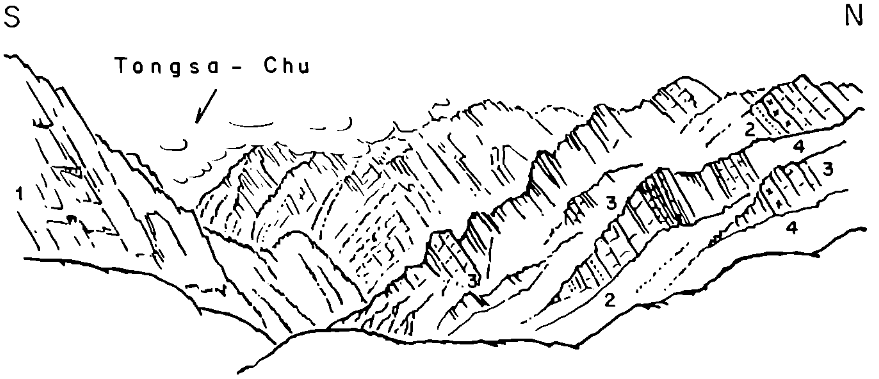


Fig. 137 *The Djüle-La zone towards upper Tongsa Chu Valley,* N Bhutan; original by A. GANSSER

1–3 as Fig. 136 4 aplite sills

granite are intercalated. Further north follow staurolite-garnet-biotite schists and biotite-psammite gneisses with intercalated marble layers. Here the staurolites are very coarse and can make up a greater part of the rock. Crossing biotite-psammite gneisses one enters rather suddenly into thick-bedded biotite-migmatite gneisses with a much more gentle northerly dip.

Towards the Djüle-La the dips steepen and marbles appear in addition to the already mentioned carbonates. The contact with the Tongsa-type gneisses is marked by an alternation of garnet-sillimanite-biotite schists and marble bands. The garnets are perfectly idiomorphic, though still somewhat rotated. Thicker marble and calc-schist horizons follow to the northeast, beginning with black graphitic slates. This zone is very well bedded and can be followed all along the northern side of the Djüle-La (Fig. 136). It extends into and over the upper Tongsa Valley with a rather constant dip and strike (Fig. 137). Where the Djüle-La carbonates cross the very wild upper Tongsa Valley there are about a dozen hot springs yielding slightly sulphurous water with CO_2, at temperatures of 55-60° C. They form local travertine basins.

North of Djüle-La the carbonate beds, alternating with schists, are cut by a larger granite mass. The intrusive contact is vertical or steeply northwards-dipping and in spite of its intrusive character is mostly concordant with the here equally steep Djüle-La zone (Fig. 138). The biotite granite is medium to fine-grained, mostly massive with inclusions of fine-grained dark biotite-psammite rocks. Nebulitic to migmatitic schlieren occur locally. Still further to the north, at the Doli-La, some biotite-psammite gneisses intruded by granites reappear, and are overlain by a larger north-dipping mass of light-grey marbles called the *Tsamba marbles*. The latter increase in thickness and form wild summits exposing an intricate pegmatite dyke system (Fig. 139). The base of the carbonate rocks is characterized by lime-silicate bands, while the higher parts turn into massive, mostly white, and often coarsely sugary marbles. The pegmatites contain some muscovite and garnets. We can follow the wild marble mountains to the ENE into the Chanka-Chu Valley where the marbles cross the valley at the beautiful place of Tsamba, the type locality for this calcareous zone. Here the marbles are about 500 m thick and consist of thick-bedded layers with thinner bedded calc-schists. Flow features are frequent in the thicker beds. The marbles are topped by biotite-garnet schists (Fig. 140); their regional dip is to the NNW.

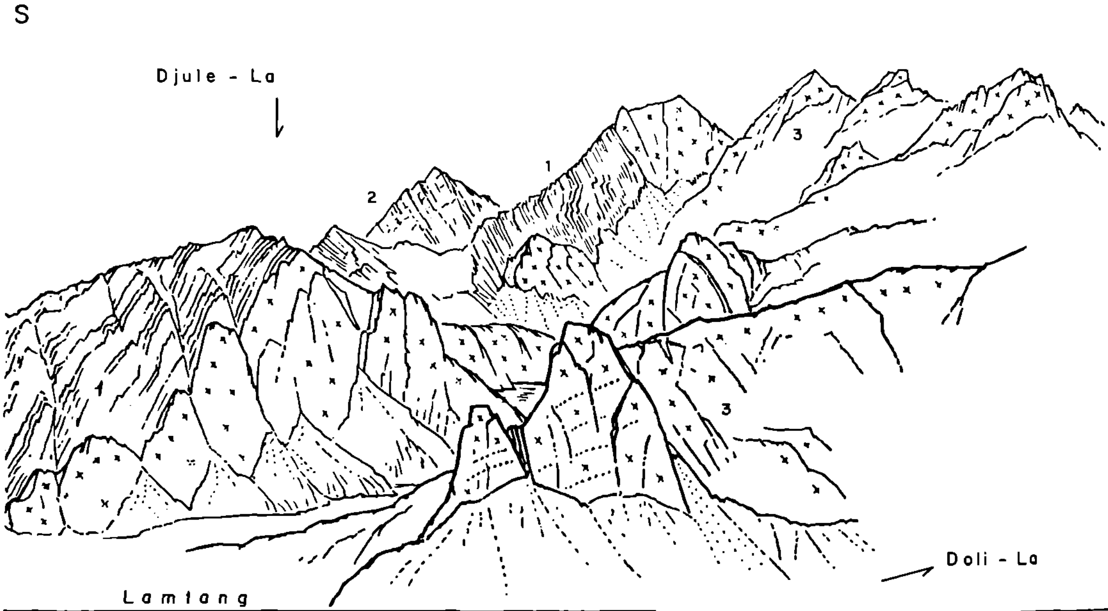


Fig. 138 *Biotite granite north of the Djüle-La zone.* Lamtang Valley, N Bhutan; original by A. Gansser

1 biotite-psammite schists 3 biotite-(muscovite) granite
2 marble zone

Melakarchung granite

Continuing upstream, after passing biotite-psammite gneisses with some migmatitic zones which

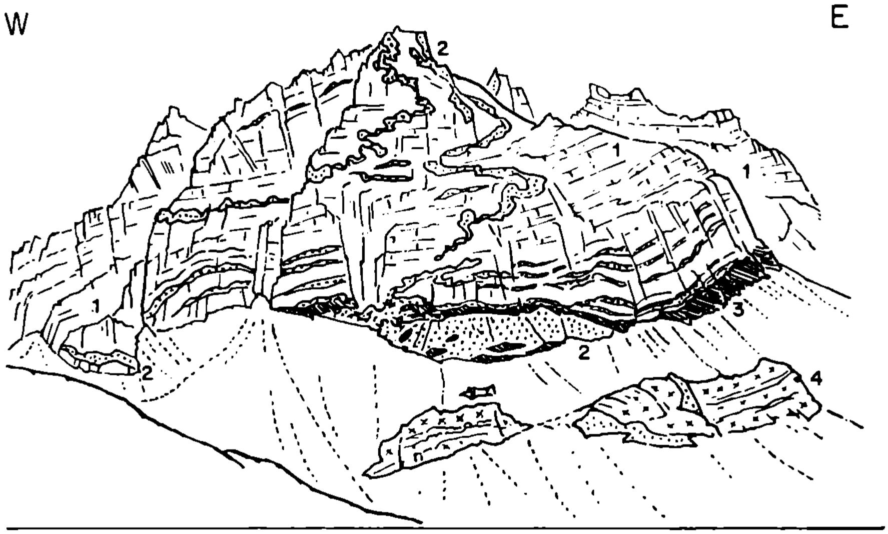


Fig. 139 *The Tsamba marbles with inticrate system of pegmatite dykes.* North Doli-La WSW of Tsamba; original by A. GANSSER

1 gray and white marbles
2 pegmatites
3 biotite-psammite gneiss
4 muscovite-biotite-granite gneiss

cover the Tsamba marbles, we enter a most complex section where psammite gneisses and, higher up, marble and lime-silicate layers are intruded by sills, dykes and larger masses of tourmaline granites, already belonging to the large *granite mass of the Melakarchung-La* at the Tibetan border (Fig. 141). The same intrusive contact zone with its array of irregular dykes was studied in the upper Melunghi-Chu Valley which from Tsamba branches from the main

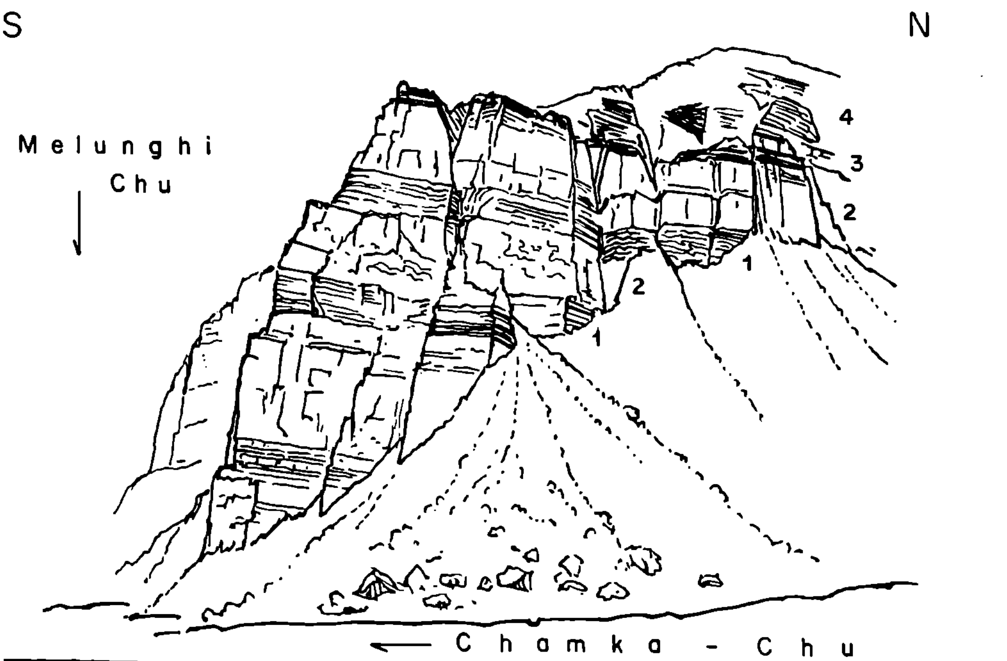


Fig. 140 *Outcrop of the Tsamba marbles.* Tsamba, N Bhutan; original by A. GANSSER

1 calc-schists
2 thick-bedded marble, often with flowing structure
3 alternating marble bands and biotite schists
4 biotite schists and gneisses

valley in a northwesterly direction. In the headwaters of the Melunghi-Chu along the Tibetan border we find the spectacular range of the Melunghi Kang (Ph. 90) which continues directly into the Gankerpünzum peak, the highest elevation of Bhutan (7500 m) (Fig. 142). The summit of Melunghi Kang is formed by bedded biotite-psammite gneisses with sill-like intrusions of tourmaline granites. The lower steep flanks and the ridge towards Gankerpünzum display masses of strikingly white tourmaline granite which continues into the Gankerpünzum peak. In some of the well-exposed nearly vertical granite cliffs one observes masses of xenoliths, mostly of undigested but sharply delineated gneisses. The marbles form constant horizons and seem more resistant to the intrusion than the gneisses, a fact muscovite. In the fine-grained rocks biotite dominates over muscovite, while medium-grained granites contain an equal amount of both micas. Aplitic granites are more restricted to the marginal zones. Here the tourmaline often shows star-like or sheave-like arrangements, with a mica-free border around the tourmaline concentration (Ph. 92). In the central part of the granites there are no xenoliths.

Further northwards, within Tibet, the amount of granite decreases again. In the very headwaters of the Kuru-Chu Valley that lies completely in Tibet and passes through easternmost Bhutan, one can observe from the Malakarchung-La larger masses of biotite schists and gneisses intercalated in the granites (Ph. 93). The imposing mountain of Künlakhari, due north of the

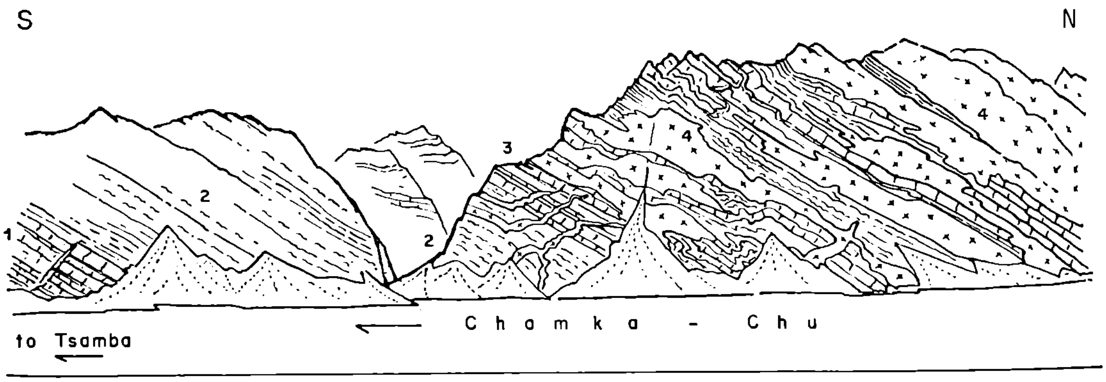


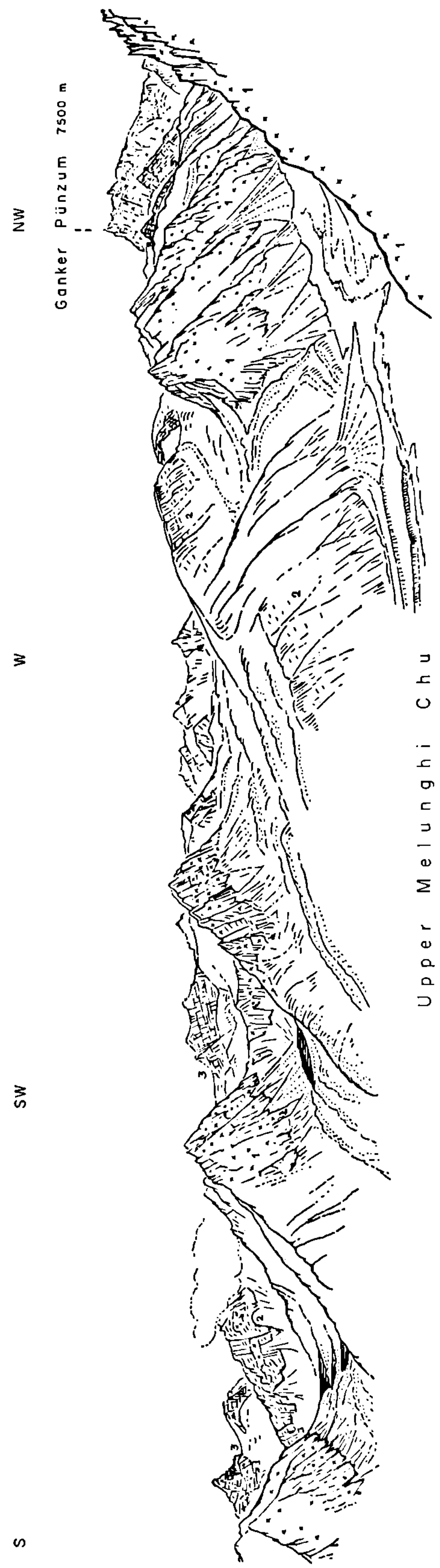
Fig. 141 *The southern contact zone of the Melakarchung tourmaline granite,* Chamka Chu Valley, N Bhutan original by A. Gansser

1 Tsamba marbles
2 biotite-psammite gneiss
3 dolomitic marbles alternating with
4 sills, lenses and dykes of tourmalin-granite, increasing northwards into main Melakarchung granite body

already described from the Nanga Parbat in the westernmost Himalayas. Below Gankerpünzum, on its southwest side, the contact of the tourmaline granite with marble zones is well exposed, displaying a wide selection of contact rocks, comparable only with the classical contact phenomena of the Tertiary Alpine Bergell and Adamello massifs. Of special interest are vesuvianite-garnet-diopside marbles with vesuvianite crystals reaching a size of 2 by 10 cm. Along the upper Melunghi Chu Valley, the marbles form a rather continuous zone of peaks following to the south of the valley (Fig. 142). Further downstream they cross the valley and connect directly with the Tsamba marbles.

The tourmaline granite intrusion increases to the north, and towards the Melakarchung-La at the Tibetan border all the head valleys and the border range consist of *young massive tourmaline granite* (Ph. 91). Here the granite is surprisingly uniform, with tourmaline, biotite and some Melakarchung-La, lies completely in Tibet. With nearly 7600 m it is the highest mountain in the eastern Himalayas east of Sikkim except for the Namche Bharwa (7755 m) at the very eastern end of the range. We were able to recognize gently northwards-dipping gneisses with granite intercalations. These probably form the crystalline base of the Tibetan sediments following still further to the north (Ph. 94). Geologically, the Künlakhari seems to be a direct continuation of the Melunghi Kang which we have already discussed (Ph. 90).

It is not known how far the tourmaline granites continue towards the east. The eastern rivers draining into the uppermost Chamka-Chu carry mostly tourmaline granite boulders, and the mountains forming the Tibetan border further to the east seem still to be built of granite. The tourmaline granite of the Gankerpünzum area is petrographically identical with the Chomolhari granite. It is completely fresh, it is not affected



tectonically and cuts through all other formations outcropping in this area (carbonate rocks and biotite schists and gneisses). Furthermore, it cuts sharply through all the folds in the limestones, schists and gneisses and also cuts the dyke intrusions visible in the surrounding rocks. All these facts point to a very young, late to post-orogenic age of the tourmaline granites, which is in line with the many similar and typical granites found as the youngest intrusive rocks in the whole Himalayan chain.

Fig. 142 *The granite and marble mountains of the upper Melunghi Chu;* original by A. Gansser

1 young tourmaline granite
2 biotite-psammite gneiss
3 limestone and dolomite marbles (Tsamba type)

CHAPTER IX

NEFA HIMALAYAS

NEFA Himalayas I call the mountains which form the *N*orth *E*astern *F*rontier *A*gency, reaching from the eastern border of Bhutan to the gorge of the Tsangpo, and including the Mishmi Hills to the east and southeast. This stretch of the Himalayas lies entirely within Assam and Tibet. Its south slopes are a densely jungled region with excessive rainfalls, and are famous for their largely uncontrolled "savage" tribes. On our compilation map the area is either left blank or coloured according to very vague geological information. In view of the proximity of the Upper Assam oilfields it is really surprising how little geological information has been published on the Sub-Himalayan foothills, not to speak of the Lower or even Higher Himalayas. The few reconnaissance surveys carried out in recent years were related to the famous and devastating Assam earthquake in 1950, while some older surveys were made by geologists attached to punitive expeditions with an understandably limited field of action.

The Sub and Lower Himalayas in the NEFA region have been subdivided into sections based on the tribes which populate the respective mountains. From the west, at the eastern border of Bhutan, to the east we distinguish the Aka Hills, the Daphla Hills, the Miri Hills, the Abor Hills along the Tsangpo, also called here Dihong-Brahmaputra, and the Mishmi Hills to the east of it. Each of the tribes has received some punitive visits, and to most of these expeditions geologists have been attached. The Aka Hills were investigated by LA TOUCHE in 1883 and the Daphla Hills by GODWIN AUSTEN in 1875. Of the Miri Hills only the lowest section of the Subansiri River, cutting through the Siwaliks, is mentioned by MACLAREN (1904). One of the best sections through the Abor Hills is described by COGGIN-BROWN (1912) who was attached to the Abor punitive expedition. He surveyed the Tsangpo (Dihang-Brahmaputra) Valley up to Singging, from where the river follows the ENE strike for a long stretch and parallels the higher NEFA Himalayas. The Mishmi Hills were cursorily investigated by MACLAREN (1903). In 1935 GHOSH made a traverse along the Dibong Valley and in 1949 DEY and CHATTERJEE visited the region northwest of the Lohit River in connection with the Minutang land-slide.

The southern border of the upper Assam basin falls outside the present discussion. Some information, in connection with the Shillong and Mikir uplifts, has already been given in the chapter dealing with the geology of the northern Indian Peninsula.

NEFA SUB-HIMALAYAS

As a direct continuation of the Sikkim-Bhutan Sub-Himalayas, the NEFA foothills are entirely formed by Siwalik-type sediments and some elevated younger terraces. As far as is known, the Siwaliks form a continuous belt to the southern Mishmi Hills, and disappear about 30 km southeast of the Dibong River.

In the foothills east of Bhutan, the Siwaliks are known from the Bhoroli River, draining the *Aka Hills* (LA TOUCHE, 1885). Conspicuous terraces, with gneisses, granites, quartzites and Tertiary sandstones as the most common gravel components form the outermost foothills and rise to 300 m above the plains. They overlap steeply (50-60°) northeast-dipping light-grey Siwalik sandstones. Northwards the sandstones become micaceous and fissile with intercalations of grey, often carbonaceous shales. The last (northernmost) visible beds are vertical, locally contorted sandstones, but the contact against the Lower Himalayan Gondwana quartzites along the Main Boundary Fault is not exposed.

Near the great *Subansiri River* the Siwalik section is complicated by steep thrusting (MACLAREN, 1904). The southern foothills, beyond the Quaternary terraces, consist here of pebbly sandstones and up to 10 m thick bands of conglomerates dipping at 60° to the northwest. The pebbles, which may attain a size of 10 cm, are composed of the same material as the recent river gravels. To the north, after a vertical tectonic contact,

follow sandstones dipping steeply to the northeast, the dip changing to northwest further northwards. Bluish clays are intercalated in the sandstones. This observed sequence probably represents an outer zone of Upper Siwaliks in steep thrust contact with the Middle Siwaliks which form the bulk of the strata outcropping in these foothills.

At the southern outlet of the *Tsangpo* (Dihang-Brahmaputra), terraces are exposed reaching 100 m above the present river level, with a pebble content similar to the recent river gravels. They border the Siwaliks, which occur here as coarse soft sandstones with small quartz pebbles and a thick section of micaceous pepper-and-salt-type sandstones often containing small nests and lenses of lignite or carbonaceous shales. The regional dip is 50° to the northwest, and conforms to the regional strike of the foothills. Here too, the contact against the older formation was not seen (COGGIN-BROWN, 1912).

Along the *Dibong River* GOSH (1935) mentions a thin band of Siwalik sandstones. They seem to continue for about 30 km in a southeastwards direction. They are completely missing in the gorge of the Lohit River at Mishmi Ghat. The relation to the older rocks is still obscure, and it is questionable whether the Main Boundary Fault persists in the same magnitude as along the foothills to the west of the Tsangpo Gorge. At the Dibong River, the Siwaliks change their strike in accordance with the eastern Himalayan syntaxis. While this change seems to be rather well outlined in the foothill Tertiaries, its effect on the older rocks is still obscure.

MACLAREN (1904) has compared the *Siwaliks* of the northern Upper Assam region with the *Tipam sandstones* of Assam. These sandstones are usually considered as the base of the Tipam "series" *(Lexique Strat. Int., Asie)* which ranges from Middle Miocene to Plio-Pleistocene—a wider range than the Siwaliks, which, excluding the Murrees, begin with the Upper Miocene. The Tipam sediments are widespread along the southern border region of northeast Assam, where they overlie the Middle and Lower Tertiaries of the Assam oil belt. Owing to a considerable gap in the foothill formations north and south of the Lohit River, a direct comparison of the Siwaliks with the corresponding sediments of the southern part of the Assam basin is not possible. Though the latter are well known and have been investigated in great detail, practically nothing is known about the lithology and faunal content of the Siwaliks of the northeasternmost Assam basin. We might perhaps venture to surmise that the different type of hinterland and the changed environment of deposition have resulted in a facies change from the northern belt to the southern Tertiary zones.

NEFA LOWER HIMALAYAS

Even compared with the Sub-Himalayas, the information about the more interior part of the NEFA Himalayas is very restricted and vague. The geological information we have was obtained in a similar way as in the foothills but here the various punitive expeditions, except the Abor trip, were limited to the outermost part of the range. The narrow but continuous belt of possible coal-bearing Gondwana rocks was the object of some further geological investigations, but little geological information came forth.

From this very scanty and patchy evidence one may assume that Gondwana-type Damuda rocks form a continuous band along the Main Boundary Fault, and are invariably thrust in a southwards direction over the Siwaliks. In the Aka Hills, along the Bhoroli River, less than 100 m of quartzitic sandstone and coarser light-grey quartzites alternate with black sandy shales, silts and dark micaceous sandstones, all more or less carbonaceous with some highly crushed coal beds. No conglomerates are mentioned. The beds strike east-west and are mostly vertical or steeply southwards-dipping. They border a badly exposed section of micaceous slaty schists, grading into greenish mica schists, strikingly similar to the Daling schists of Sikkim. No carbonate rocks were noted in this section, nor was the contact with the coal-bearing quartzites observed. Like the latter, the schists are practically vertical and strike east-west.

Very similar Damuda-type coal-bearing quartzitic sandstones were reported from the Daphla Hills. Here, too, they are practically vertical and strike parallel to the foothills. They were found again in the lower section of the Tsangpo (Dihong-Brahmaputra) Valley, where they consist of highly tectonized coals within quartzites and shales, still with near vertical dips. These steep sections, apparently quite constant, contrast somewhat with the flatter north dips of the more western sections. From the Subansiri River, boulders of fossiliferous hard black marly limestone and calcareous sandstones were reported (MACLAREN, 1904). The fairly rich fauna points to a Permo-Carboniferous age, and resembles that of the Lower *Productus* limestones of the Salt Range. In a western tributary of the lower Tsangpo, COGGIN-BROWN found rolled, dark bluish grey, slightly arenaceous limestones with crinoids and other indeterminable fossil remains. These boulders could be derived only from the base of the Gondwana detrital rocks, a fact quite important considering the similar boulders mentioned from the Subansiri River. The latter were believed to come from the headwaters of the river, which rises from the Tibetan plateau, although it seems more likely to trace the source

of the Subansiri boulders also to the base of the Gondwanas rather than have them travel over such an excessive distance. The fact that a facies reminiscent of the Salt Range reappears far in the eastern Himalayas is of considerable importance.

Abor Volcanics

The Gondwana rocks in the lower Tsangpo (Dihong) are followed northwards very unexpectedly by a volcanic sequence of great significance. The contact is transitional, and Gondwana-type quartzites are found interbedded in the volcanics. The latter increase until they form a comprehensive section. Most typical are dark-green to reddish trap-like amygdaloidal lava flows, with agglomerates and some red jasper bands. Thin quartzites are locally intercalated. They dip irregularly at 50° to the northeast, and higher up to the northwest. They can be observed over a distance of about 20 km. They are followed by badly exposed sericite schists with quartzites, some slates and brecciated dolomitic limestones showing steep irregular dips. This part of the section resembles to some extent the Baxas or the Dalings. Upstream one finds a second belt of volcanics similar to the types met in the lower section, except for more frequent intercalations of reddish white quartzites. Unfortunately the contact relations to the schistose sections are unknown.

The Abor volcanics seem rather widespread in the easternmost Lower Himalayas. A western extension was observed by GODWIN AUSTEN in the Daphla Hills, where he described Gondwana coal seams and quartzites related to dark-green rappean rocks. There seems little doubt that the Abor traps are related to the Gondwana formations in a similar way as the Panjal traps in the Kashmir region. A lithological similarity of the Abor volcanics with the Rajmahal traps of the eastern Peninsular shield north of Calcutta has been stressed by COGGIN-BROWN. The latter are intercalated in carbonaceous shales with Jurassic plants, and therefore most likely younger than the Abor volcanics. It seems somewhat surprising that the Abor volcanics have not been correlated with the Panjal traps of Kashmir, with which they have some lithological similarity, particularly if the agglomeratic intercalations are considered, and which may after all have about the same age.

Up river in the Tsangpo, above the second intercalation of Abor volcanics, a semi-metamorphic sequence follows for a distance of about 40 km. Again the contact relations are obscure. Beginning with badly outcropping dark-grey or coloured slates and quartzites, a thick argillaceous sequence with quartzitic intercalations gradually becomes metamorphosed, grading into phyllites and mica schists. Twenty kilometres southeast of the major river bend flaggy dolomite horizons appear in the schistose zones. From eastern tributaries some boulders of augen gneiss and garnetiferous schists are brought down. In general the schistose layers are dipping at 30-40° to the north, but locally steep southerly dips have been noted.

Towards the main bend of the lower Tsangpo (Dihang) River the metamorphism increases rather suddenly and one enters a section of biotite-muscovite schists, micaceous quartzites, and actinolite schists with associated calc-schists. From here the Tsangpo (Dihang) River runs for about 95 km parallel to the strike of the Higher Himalayas until it breaks through the main range. COGGIN-BROWN's expedition only reached this point, and the higher regions remain geologically unknown.

It is difficult to unravel the structural features met along the Tsangpo (Dihang) Valley. The frequent repetitions of similar horizons suggest isoclinal folding or imbrication. Most of the dips are to the north, suggesting generally southwards-directed folds and thrusts. The difficult, highly jungled terrain demands much additional information before a more comprehensive picture of this remote region can be given.

On very general lines, it seems likely that regional metamorphism increases from the south to the north, and that some of the sections are probably reversed. A relatively sharp increase in

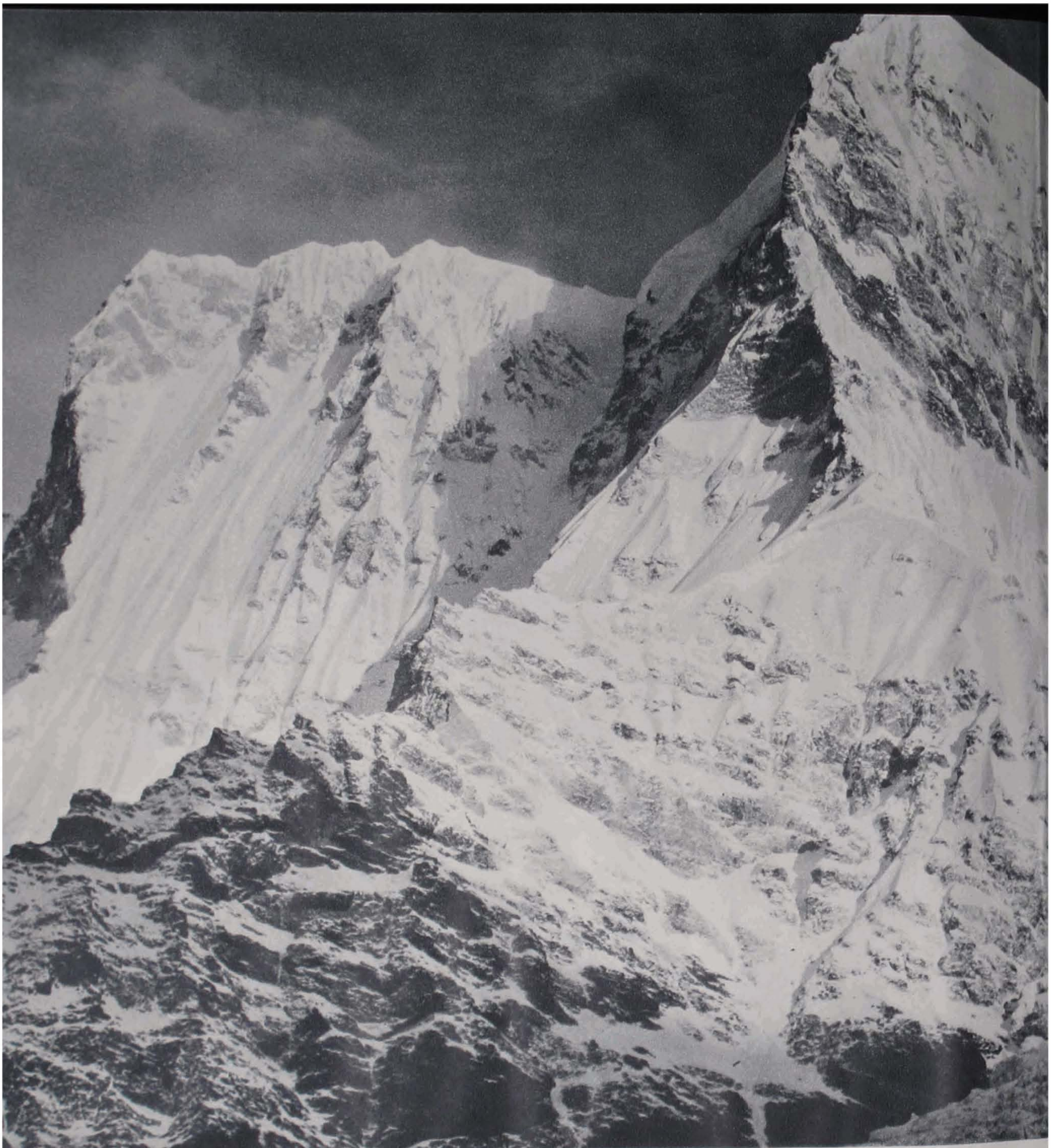
Phot. 82 *Eastwards-increasing marble bands in the southwest wall of Tserim Kang peak* (eastern Chomolhari Range). The granite sills are restricted to the upper part of the mountain, while thick marble walls form the base. Changmutang, NW Bhutan (phot. A. Gansser)

Phot. 83 *The double summit of Masa Kang* (7165 m), seen from the SE. Migmatites with locally mobilized biotite granites, cutting discordantly through the gneisses. North Bhutan (phot. A. Gansser)

Phot. 84 *Garnet amphibolite. South of Masa Kang (N Bhutan).* The garnets (1) form inclusions in large green hornblende crystals (3) with rims of andesine-labradorite (2). Enl. 15×

Phot. 85 *Typical migmatite gneiss of the Masa Kang region,* with small tourmaline-aplite veins. Local mobilized lenses and layers of fine aplite-granite can increase to larger bodies of cross-cutting granite. SE of Masa Kang, North Bhutan (phot. A. Gansser)

Phot. 86 *Tourmaline granite dyke intruding banded migmatized biotite-psammite gneisses.* The dyke has an aplitic border zone, sending small apophyses into the country rock. SE Masa Kang. N Bhutan (phot. A. Gansser)



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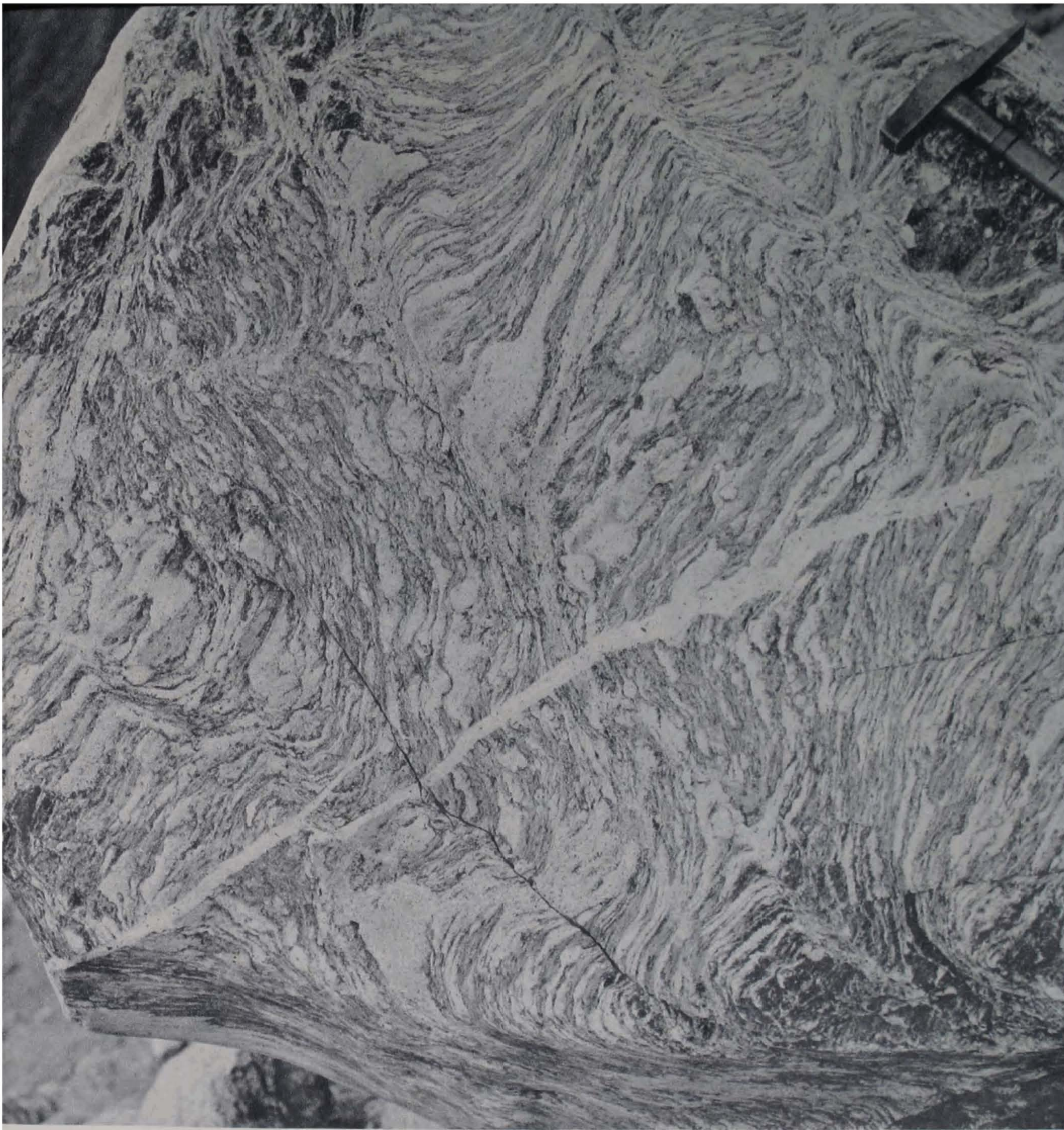

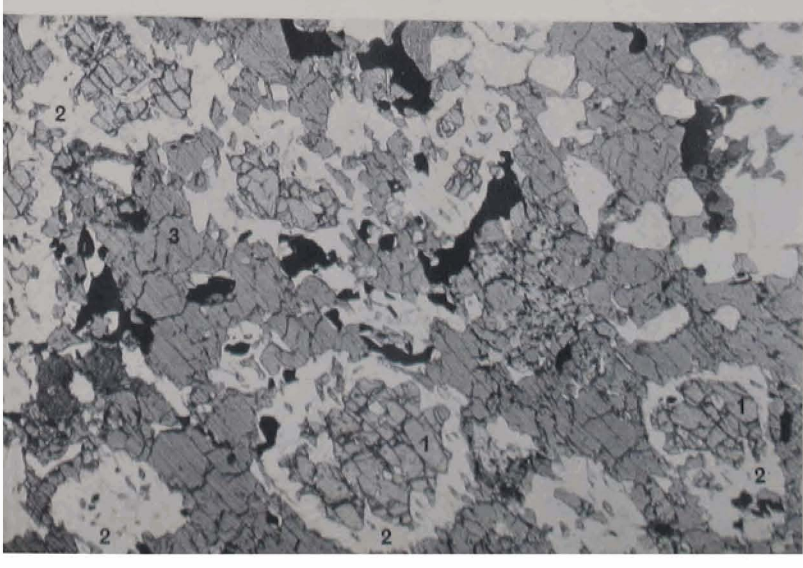
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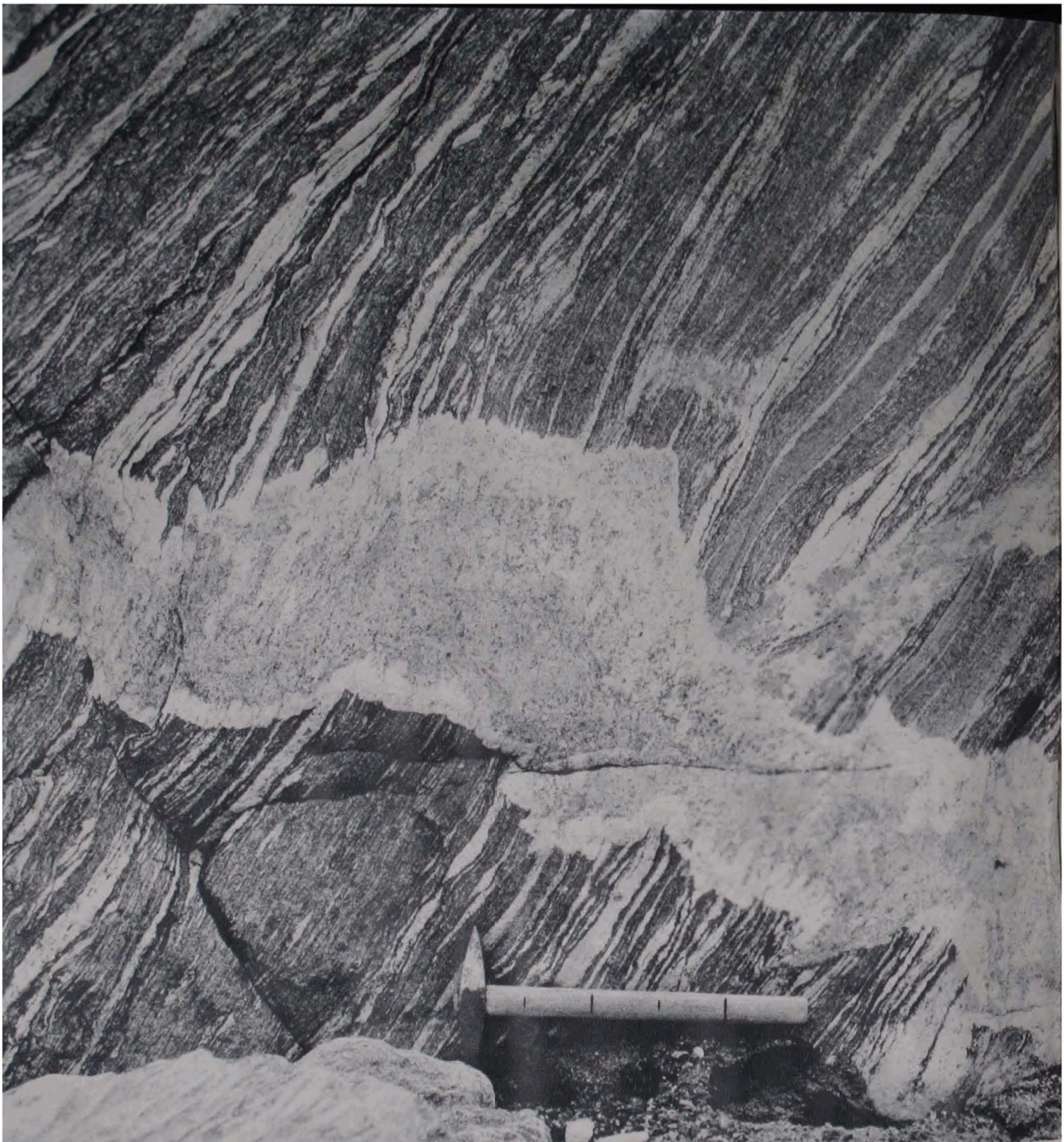

metamorphism was noted at the foot of the Higher Himalayas, just south of the sharp major bend of the river. This sudden change could very well coincide with a major thrust, and one may venture *to place here the Main Central Thrust*, limiting the Higher Himalayas to the south.

Southeast of the Tsangpo (Dihang) Valley, the *Mishmi Hills* are a geologically most important area, considering the fact that here the so far ENE-striking ranges change around a still very obscure eastern syntaxis into southeast strike. We have already noted that the Siwaliks follow the foothills for about 30 km to the southeast of the Dibong River, after which the rocks of the Lower Himalayas border directly on the Assam plains. Along the *Dibong River*, after crossing the small stretch of Siwaliks with soft micaceous sandstones and sandy shales with fragments of lignite, one reaches a thick body of banded greenish and pink quartzites. The contact, though badly exposed seems to be a major steep thrust. High river terraces, some 200-300 m above the stream level, border the valley. No trace of Gondwana-type formations were observed. The quartzites gradually become increasingly metamorphosed, altering to schistose micaceous quartzites. Up river, banded biotite gneisses appear, alternating with greenish schistose quartzites and some carbonate bands. The regional dip of the gneisses and quartzites is 45-50° in a northerly direction. Further to the northeast follow amphibole schists and hornblende gneisses with associated graphitic garnet schists, garnet-chlorite-sericite schists and some crystalline limestones. Greenish quartzites are still intercalated. The whole is tectonically disturbed. The regional strike is again east-west, and where the beds are normal they dip at 50° to the north. Still further north, the schists are invaded by hornblende-granite gneisses and hornblende granites which seem to be rather widespread in the headwaters.

The Dibong section differs completely from the Tsangpo (Dihang) River region described above. The northeastern strike of the latter has turned east-west, and the Gondwana-type rocks with their widespread Abor volcanics seem to be missing. A gradual increase in metamorphism is evident, beginning with the low-grade quartzites below and, considering the rather constant northerly dip, ending with the granitic rocks in the structurally higher levels.

A major disturbance must divide the metamorphics of the Mishmi Hills from the Abor region. Local tectonized sections have been noted, and some may be of regional importance. We will note in the following that in the southeastern Mishmi Hills very similar conditions are met.

The hills surrounding the embayment of the *Lohit River* further to the southeast were investigated in 1949 by Dey and Chatterjee (Dey and Saha, 1954). From these so far completely unknown regions, only metamorphic rocks have been reported and the thick quartzite sections of the Dibong River were not met. Siwaliks are completely missing. The foothills consist of garnetiferous mica schists and muscovite gneisses often staurolite-bearing. Crystalline limestones and calc-silicate rocks are interbedded. Layers and lenses of granite gneisses seem to form intrusions into the schists. The garnets are rich in quartz and ore inclusions, a fact frequently observed in the garnets of similar schists in the Himalayan crystallines. In some of the garnet-staurolite schists both garnet and staurolites have been rotated through 180°. The calcareous intercalations are rich in grammatite, actinolite and green amphibole. Together with these occur white coarse-grained marbles containing some quartz and microcline grains. The regional dip of the metamorphic rocks is towards the northeast; the strike conforms to the trend of the foothills. Further inland the strike becomes more east-west, suggesting structural complications which must be expected in this region.

Towards the northeast, the schists and schistose gneisses are replaced by dioritic gneisses, composed predominantly of andesine and hornblende. They resemble the hornblende-granite gneisses of the upper Dibong River. Plagioclase usually constitutes over 70% of the rock, with some interstitial quartz. Associated are granodiorites and granites. Some amphibolitic rocks form inclusions in the dioritic gneisses. Ultrabasics in the form of serpentine with asbestos veins were noted along the contact between the schists and the dioritic gneisses.

Nothing can be said with certainty about the general geological position of these metamorphic rocks. They can be compared with many of the Precambrian sections of the base of the Higher Himalayas. One may stress the fact that Gondwana-type sediments or even rocks corresponding to the Dalings were not observed. This could mean that the metamorphic rocks of the Mishmi Hills are not a direct continuation of the Lower Himalayan formations, but reflect a belt of old metamorphic and igneous rocks which originated further to the north and are striking from northwest towards the southeast, past the eastern end of the main Himalayan range. They would thus belong to *structural elements east of the Eastern syntaxis* or form the eastern "branch" of such a syntaxis, representing in this case elements of the Higher Himalayan metamorphics.

NEFA HIGHER HIMALAYAS

We may not be far from the truth if we state that the Higher Himalayas of the NEFA region are

geologically unknown, or that at least practically nothing geological has so far been published on this part of the range. Climatic and political difficulties may be the main reason, although the passes that cross this part of the high range are the lowest in all the Himalayas.

The northern slopes of the high range were explored by British botanical and ornithological expeditions during the years 1934, 1935, 1936 and 1939. From their photographs, some picturing probably for the first time such important mountains as Namche Barwa and Gyala Peri in the Tsangpo Gorge, geological information can be deduced (Kingdon Ward, 1936; F. Ludlow, 1938, 1940).

flowing from south of Lhasa in an easterly direction, has approached the range (the watershed) to as near as 15 km and now follows its northeastern trend. The relatively low elevation at which the passes cross the main range is surprising: the tree-studded Tum-La is only 3600 m high, and the more eastern Shoka-La apparently still lower. We have here one of the lowest passes crossing the whole Himalayan range, similar to or even lower than the Zoji-La in Kashmir (3529 m), and only 600 m higher than the Tsangpo River which meanders in a rather steep gravel-filled valley, flanked by impressive terraces.

On the very eastern end of the main Himalayan range, where the Tsangpo turns from its north-

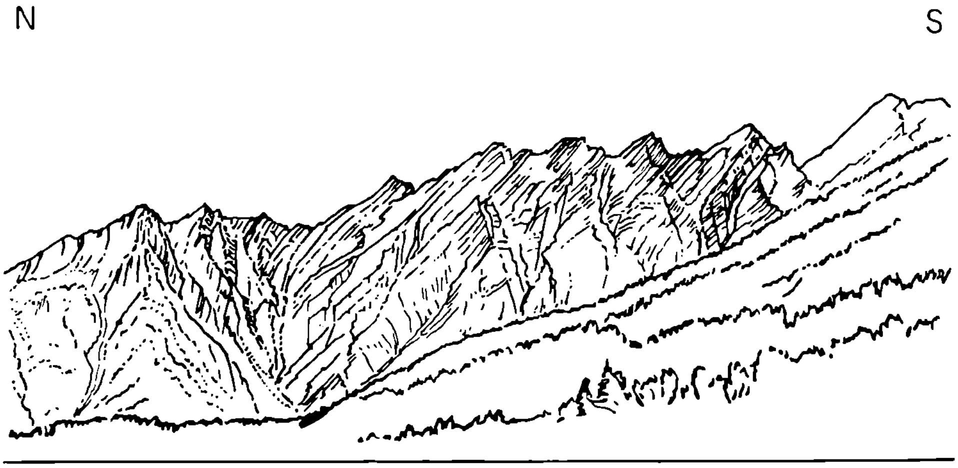

Fig. 143 *The north spur of Namche Barwa,* Tsangpo Gorge at Gyala, NE Himalayas; drawn after photo by G. Taylor (*Himal. Journ.* vol. XII, 1940). Note clearly visible north dip of gneissic north flank of Namche Barwa, steepening northwards

East of Bhutan, the large Subansiri River cuts the main range and sends its headwaters far into Tibetan territory, pushing the actual watershed near to the Tsangpo River, similar to the Arun in E Nepal (Pl. I A). Between Bhutan and the Subansiri River the Kangdu massif (7089 m) forms the only major culmination. It forms a marked southwards-directed spur and it seems possible that this culmination coincides with a southwards-extended "bulge" of the main thrust zone.

The only trafficable trade route from south to north runs along the eastern frontier of Bhutan; it was used by the Dalai Lama for his flight in 1959 and by the Chinese troops for their southward advance three years later. Further east no major trade routes cross the range, and this fact accounts also for the little-known aspect of this part of the Himalayas.

From the Subansiri River to the ENE, the main range is surprisingly straight, and no river flowing to the south crosses it. The Tsangpo,

easterly course into a south and then southwestern direction, we meet the *highest elevation of the whole eastern Himalayas* (east of Kangchendzönga) in the still practically unknown *Namche Barwa* (7755 m). Facing this on the north of the deep Tsangpo Gorge is the equally little-known Gyala Peri of 7150 m. As the counterpart to the famous Indus Gorge at the western end of the Himalayas north of Nanga Parbat, the Tsangpo cuts exactly through the highest culmination of the eastern end of the Himalayas. Down to Pe or Timpa, just WSW of Namche Barwa, the Tsangpo flows placidly in a gravel-filled, though rather steep-walled, valley. From here downstream, the river, which was previously over 1 km wide, suddenly narrows to a mere 90 m and tumbles through a deep gorge with enormous boulders in most impressive cataracts. (Ludlow, 1940). Above this gorge river terraces occur at an elevation of 200-300 m above the wider valley level. This most drastic morphological change

seems to reflect a very young uplift of this part of the range, coinciding with the culmination of Namche Barwa. We may recall that no such fall was observed along the Indus River where it cuts through the Nanga Parbat uplift.

Judging from photographs by G. TAYLOR (LUDLOW, 1940) the northern spur of Namche Barwa exposes steep north dips, steepening from south towards north (Fig. 143). While discussing the Lower Himalayas we have already noted how COGGIN-BROWN reached high grade metamorphic rocks in the lower Tsangpo (upper Dihang-Brahmaputra) Valley, which could form the base of the Main Central Thrust sheet. The thrust seems to strike in an ENE direction, and the river runs parallel until its break through. The regional dip is to the NNW, and judging from the rather straight aspect of the main range probably changes little. This northern dip is still well visible on the northern side of Namche Barwa, and it seems most likely that Namche Barwa is built of crystalline rocks at least on its southern side. On the evidence of the photograph of TAYLOR (in LUDLOW, 1940), it seems unlikely that the well-bedded sediments of the Everest type form the northern spur, and therefore, until more information is available, we assume that the whole Namche Barwa is predominantly built of metamorphic rocks. On its northern neighbour, Gyala Peri, on the other side of the wild Tsangpo Gorge, a northwards dip seems detectable, though it is less clear than on Namche Barwa. One may further suggest that the northeastern strike of the high range changes east of the Namche Barwa culmination into a more northerly direction in connection with the certainly major tectonic disturbance of the eastern Himalayan syntaxis. To what extent we deal with a real syntaxial bend will only be known when geological information becomes available. North of Gyala Peri follows the large Yigrong River, which joins the Tsangpo just north of its major bend. This river, investigated for the first time by KINGDON WARD (1935), is reported to be flanked by impressive snow mountains, particularly on the southern side of the ESE-flowing river. At first these ranges strike EW, then they change to a SE direction, and finally run parallel to the southeasterly directed metamorphic ranges which close the Assam basin in the east. A major fault or thrust zone seems to separate these ranges from the main Himalayan structures.

CONCLUSIONS

"It is realised that there is often danger in early generalisation from incomplete observations such as are made on traverses. The Himalaya are so vast, however, that years will elapse before they are mapped geologically in detail, and it seems desirable therefore to place such observations on record, so as to build a scaffolding for the later formulation of geological structure which will eventually emerge from detailed work. Such results may also have a bearing on the understanding of the geology of the small areas where mapping is at present in hand." AUDEN: *Traverses in the Himalaya* (1935).

In the foregoing chapters I have dealt with the geology of the Himalayan ranges and have discussed the various regions as more or less well-outlined geographical units. In the following I shall endeavour to condense the facts into a more regional, comprehensive picture. I am fully aware that certain deductions are based on very vague information, and that the lack of stratigraphical control in the wide expanses of the Lower Himalayas is a major handicap. The discussion is illustrated by the geological and tectonic general map of Plate I, A and B, and by the regional cross sections A, B and C on Plate II.

In the Himalayan mountains rocks belonging geologically to the shield of peninsular India play an important role. This is particularly true in the Lower Himalayas and in the large crystalline thrust mass of the Higher Himalayas. Shield elements, with their Precambrian stratigraphical and structural history, have been involved in the much younger (Upper Cretaceous to Recent) Himalayan episode. In some areas the original structural grain and lithological composition have been clearly preserved; in others the structures have been reactivated, and in others the subsequent orogeny has fully obliterated the older fabric of the rocks.

CHAPTER X

GEOLOGIC HISTORY OF THE HIMALAYAS

Precambrian to early Cambrian history

We are justified in tracing the Himalayan history back to the latest Precambrian and earliest Cambrian — to the times following the important orogeny which built the Aravalli Ranges. The structures of this early, pre-Vindhyan, orogeny have, however, been incorporated in the Himalayan folding phase, and the structural grain of the Aravallis has influenced the tectonics of the Himalayas in many ways, as was stressed by AUDEN in 1935. On the regional structural map (Plate I, B) we can see how the Aravalli Ranges strike at right angles to the Himalayan trend, and it seems reasonable to assume that the Aravallis continue below the south-vergent structures of the Himalayan mountains. The Precambrian history of the rocks of Peninsular India shows us, therefore, the course of the history of the oldest crystalline basement of the Himalayan chain.

The Precambrian rocks of the Indian shield have undergone several orogenic phases. Only now, with the help of absolute age determinations, and more detailed investigations, is their story being gradually outlined. :The older Archaean rocks were altered repeatedly before the transgression of the predominantly detrital Aravalli sediments. Carbonate deposition was missing during the greater part of the Archaean era, but the record of its sudden appearance is seen in the conspicuous Raialo marbles, placed by some authors at the end of the Archaean and by others at the beginning of the Algonkian or Purana era. In the subsequent deposits carbonates play an important role, and are preserved as marbles and calc-schists associated with the argillaceous and arkosic sediments. Major facies changes seem unlikely between the sediments of the shield area and those of the Himalayas in pre-Vindhyan times.

Most of these sediments were altered during the Aravalli orogeny, when the most outstanding mountain ranges of Peninsular India were formed. However, the Aravalli Ranges probably did not reach the magnitude of Alpine ranges as is claimed by some authors. The following interval at the end of the Archaean marks the longest hiatus in the geological time scale.

These more or less metamorphosed rocks form the old crystalline basement of the Himalayas, and although they have undergone a strong Himalayan orogeny, they have preserved much of their original composition. This is witnessed by the schists, gneisses and associated carbonate rocks, and the latter especially must be distinguished from similar horizons belonging to the Palaeozoic.

Gneisses, migmatites, crystalline schists, thick quartzites and some tectonized granite intrusions form the basal part of the Main Central Thrust sheet, and may be compared with the Archaean rocks of the Indian shield. In the upper part of the crystalline thrust mass follow conspicuous marble and lime silicate horizons with amphibolites and psammite gneisses, and huge schistose sections which reflect the Algonkian (Purana) part of the shield rocks. In Kashmir and north of the Main Central Thrust of the Higher Himalayas, Cambrian faunas are found in low to non-metamorphic rocks covering the crystallines and confirm a Precambrian age for the several thousand metres of crystalline rocks underlying the fossiliferous beds.

The Aravalli orogeny was the last major tectonic event in Peninsular India and was followed by Vindhyan sedimentation, when a huge pile of surprisingly uniform, mostly terrestrial, sandstones was laid down. Except for some late Aravalli disturbances these have not been tectonically affected. In contrast to the older shield rocks, we may assume that the Vindhyans were subject to facies changes and became more marine away from the shield. Marine incursions are demonstrated in the northern shield by the peculiar and still doubtful fossil traces in the sandstones and shales, as well as in the limestone horizons with a stromatolitic aspect. The change from continental to marine environment must have produced, at least locally, evaporitic deposits

such as those of the Salt Range. It is generally assumed that the Saline Series and its cover, the Purple Sandstones, represent part of the Vindhyan sedimentation.

We know little about the extension of these saline beds. Their correlation with the Hormuz formation of the Persian Gulf is most plausible. Their eastwards extension into the Himalayas remains an unsolved problem. It could be assumed that a saline belt borders Peninsular India along its northern edge, and is now covered by the frontal Himalayan thrusts. We have tentatively suggested that such saline horizons, if present, may have had a substantial influence in the formation of the deeper Lower Himalayan thrust sheets, though admittedly no such saline beds were found in the deep, presumably autochthonous windows of this belt. We may stress the fact that in these windows rocks with only weak, or no, metamorphism are exposed, and nowhere do crystalline horizons outcrop in the deepest autochthonous or parautochthonous sections except in the steep Nanga Parbat syntaxial core.

All along the Lower Himalayas the thick argillaceous formations, with some quartzites and limestones, may be the marine equivalent of the Peninsular Vindhyans. The recent discoveries of stromatolitic horizons in the Lower Himalayan section lends further support to this thesis, and suggests a late Precambrian to Cambrian age. Some of these limestones form surprisingly thick sections, reaching several thousand metres in the central Himalayas southeast of the Sutlej River. They are frequently overlain by equally thick quartzite sections, assuming that the sequence is normal.

The question has risen whether this thick section of mostly unmetamorphic or only slightly metamorphic (epi-metamorphic grade) sediments should be correlated with that of the Krol belt of the outer[1] side of the Lower Himalayas. In spite of the characteristic sequence of limestones and quartzites (Krol-Tal), the lithology as well as the stromatolitic horizons suggest an older, and as already mentioned, probably late Precambrian to Cambrian age. This sequence may be contrasted with the thick argillaceous sequence of the Higher Himalayas which belongs to a northern, inner belt related to the Tethyan basin and represents the basal, late Precambrian, sediments.

The thick Lower Himalayan limestones suggest a rather quiet sedimentation in a shallow sinking basin with stromatolitic growths. The basin probably became deeper towards the north, away from the Peninsular shield. The great thickness of associated quartzites is surprising and still difficult to explain. The over 3000 m thickness of detrital rocks must have been derived from a quartz-rich source, but was most probably reworked and not derived directly from crystalline rocks, as the few, but important, conglomerates contain no metamorphic or igneous components and consist almost exclusively of quartzites. The presence of such conglomerates (with rounded boulders reaching head size) is unusual in normal limestone and dolomite successions. Quartzites are widespread in the Precambrian crystalline thrust sheets of the Himalayas, but, except in the Alaknanda (upper Ganges) area where they are 9000 m thick, they mostly alternate with more argillaceous beds altered to gneisses. Gneiss components are, however, rare or absent in the coarser clastic horizons of the older sedimentary cover.

Locally, and mostly associated with the quartzites, there are thick sections of tuffaceous beds, altered into chloritic schists with some epidioritic intercalations representing actual flows. Tuffs and flows were most likely submarine. I have already drawn attention to the fact that similar epidiorites and amphibolites are frequently associated with the Lower Himalayan thrust sheets and occur again at the base on the Main Central Thrust in the central Himalayas.

[1] Outer means here the frontal belt towards the S and SW and following the Siwalik zone. Inner means towards the N or NE, towards the root zone.

Phot. 87 *Aplitic tourmaline granite dykes cutting banded migmatitic biotite gneisses* with a layer of fine biotite-psammite-gneiss. The latter clearly shows displacement by a fault, along which the granite dyke intruded. SE Masa Kang, N Bhutan (phot. A. Gansser)

Phot. 88 *Fine aplite granite sill fingering out into banded migmatite gneisses* (sill about 30 cm thick). SE of Masa Kang, N Bhutan (phot. A. Gansser)

Phot. 89 *Sills of aplitic granite* and some pegmatites in biotite-psammite gneiss are cut by younger fine-grained biotite granite dykes (d). North of Masa Kang below Toma-La. N Bhutan (phot. A. Gansser)

Phot. 90 *The spectacular east wall of the Melunghi-Kang* in the head of Melunghi-Chu. The summit (dark rocks) consists of injected biotite-psammite gneisses, while the steep iced wall and ridge to the left are formed by white tourmaline granites with swarms of large angular gneiss xenoliths. Marbles outcrop at the very base of the wall. Regional dip is to the north. NE Bhutan (phot. A. Gansser)

Phot. 91 *White, homogenous tourmaline granite on Mela-karchung-La.* Peak to the left formed by large xenolith of dark biotite gneisses (phot. A. Gansser)

Phot. 92 *Starlike arrangement of tourmaline needles in biotite-(muscovite)-tourmaline granite* of the Melunghi Chu region, near contact with marble zone. Star mesures 5 cm

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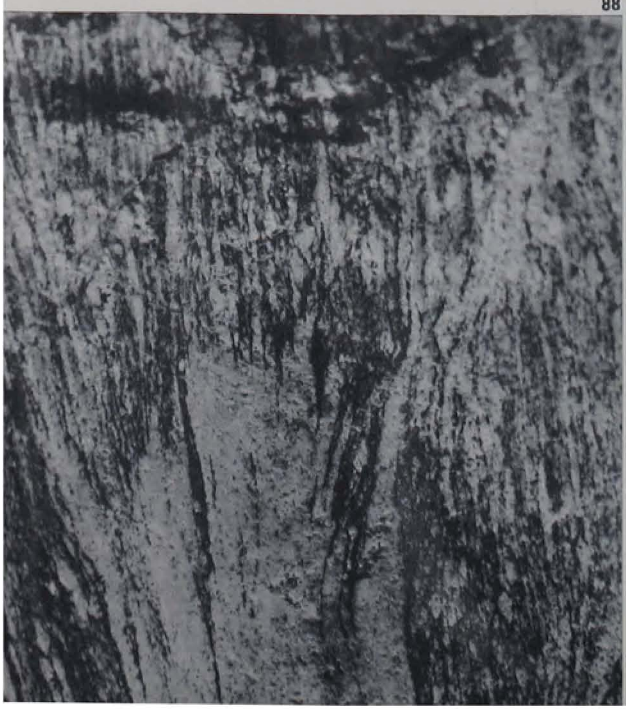

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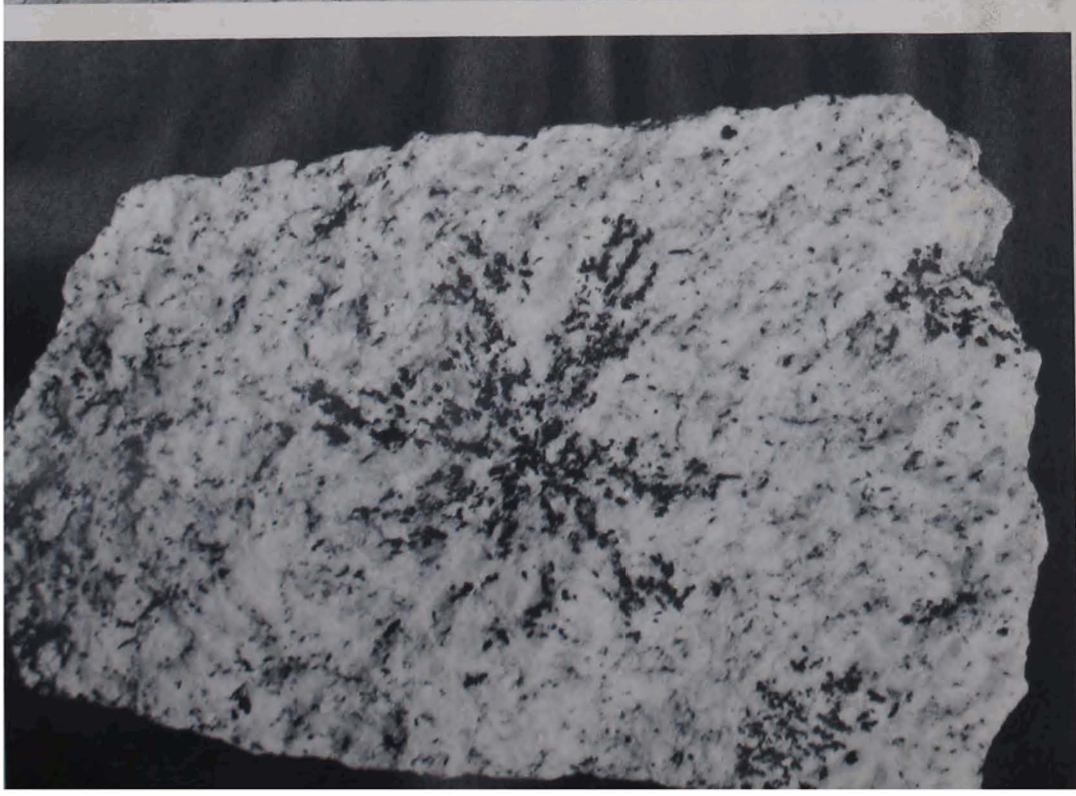


Late Precambrian to Cambrian deposits form equally thick, mostly well-bedded, argillaceous sections in the Higher Himalayas, where they lie normally above the large crystalline Main Central Thrust mass and form the base of the Tethys-type sediments. This inner belt is separated from the outer belt by the Main Central Thrust, which shows NS displacements of the order of one hundred kilometres or more. This thrust diminishes towards the Kashmir region, and it is here that the Tethys sediments have crossed the central divide and cover the Lower Himalayas (see sketch map, Fig. 145).

In the Higher Kumaon Himalayas the 5000 m section of monotonous, more or less calcareous, phyllites with thin quartzite bands and some greenish, probably pyroclastic, intercalations (Martoli and Garbyang formations) does not show the conspicuous differentiation into limestones and quartzites as in the corresponding sections of the outer belt of the Kumaon Lower Himalayas. The sediments of the inner belt seem to have been deposited into a somewhat deeper basin. Except for their rather high carbonate content they resemble certain Daling schists in the eastern Lower Himalayas, though most probably the latter are somewhat older and do not reach into the Cambrian.

It is a most important fact that here, in the Higher Kumaon Himalayas where the most complete section is represented, there is a gradual passage from the underlying crystalline rocks into the overlying sediments, and no unconformity is visible. The metamorphism of the crystalline rocks has decreased, and, passing through a zone with characteristic biotite porphyroblasts in phyllitic schists (Bhudi schists), we reach the phyllitic calcareous sediments which contain pre-Ordovician fossils in their upper beds (Garbyang formation).

A local unconformity has been found below the Ralam conglomerates. The conglomerates consist only of quartzitic pebbles and could coincide with the Precambrian-Cambrian boundary, and thus be of more than local importance. Their restricted development, however, suggests rather an internal local accident and not a major unconformity between the Precambrian floor and the Cambrian cover as suggested by BORDET (1961). Such a major unconformity, resulting from an older orogenic phase must be hidden within the still little-known crystalline sheet and obliterated by the young Himalayan orogenic phase.

Palaeozoic and Mesozoic to Recent history

The *Palaeozoic history* of the Himalayas is more differentiated and varies considerably from the outer to the inner zones of the range. In northern Peninsular India the Vindhyan sedimentation was followed by a long period of emergence which lasted until the Upper Carboniferous. The onset of Gondwana sedimentation is indicated by the well-known glacial deposits. In this long interval conditions in the Lower Himalayas were not unlike those of Peninsular India, except for the Punjab and Kashmir Himalayas where the Tethys sediments of the inner or northern Himalayas transgressed south over the central crystalline ranges. The only dated post-Cambrian to pre-Gondwana rocks so far found in the Lower Himalayas outside Punjab are the Silurian Pulchauki beds of Central Nepal and the newly discovered Tang-Chu (Devonian?) in Central Bhutan. Both occur in synclinal positions above metamorphosed thrust masses which partly cover the deeper underlying sedimentary rocks.

The wider Simla region is geologically well known and presents the typical conditions. Late Precambrian to Cambrian slates and limestones (with stromatolitic horizons) are directly covered by the famous Blaini boulder beds, which can be correlated with the Upper Carboniferous Talchir tillites of the Peninsular shield and the Salt Range. While discussing the Blainis I have stressed the fact that not all boulder beds correspond to tillites, and that certainly not all are Blainis. The observation remains, however, that Gondwana-type sedimentation begins in the Upper Carboniferous with coarse clastics which are reminiscent of tillites and are followed by frequent intercalations of pyroclastics and volcanics—the Panjal traps—which, in their uppermost horizons, expose marine incursions indicating the proximity of the northern limit of the Gondwana land mass. It is interesting to note that Panjal traps are restricted to the western and easternmost Himalayas (they are seen in the latter area as the Abor volcanics).

Gondwana influence in the Lower and even Higher Himalayas is well known. The characteristic Damudas were investigated at an early date because of their coal content. The recognition of the Damudas with a tillitic base in the Lachi region of the border between north Sikkim and south Tibet, well within the Higher Himalayas, suggests a considerable northwards extension of the Gondwana sediments, especially as we must assume here a NS displacement of at least 100 km. The approximate extension of the tillites and related Gondwana sediments into the Himalayas is shown in Fig. 144.

In the Lower Himalayas southeast of the western Himalayan syntaxis the basal Gondwana Blaini beds are followed by a conspicuous sedimentary section which is well exposed in the Krol belt. Except for indeterminable fossil remnants in the highest beds, the Krol rocks have so far yielded no faunas, a fact of significance

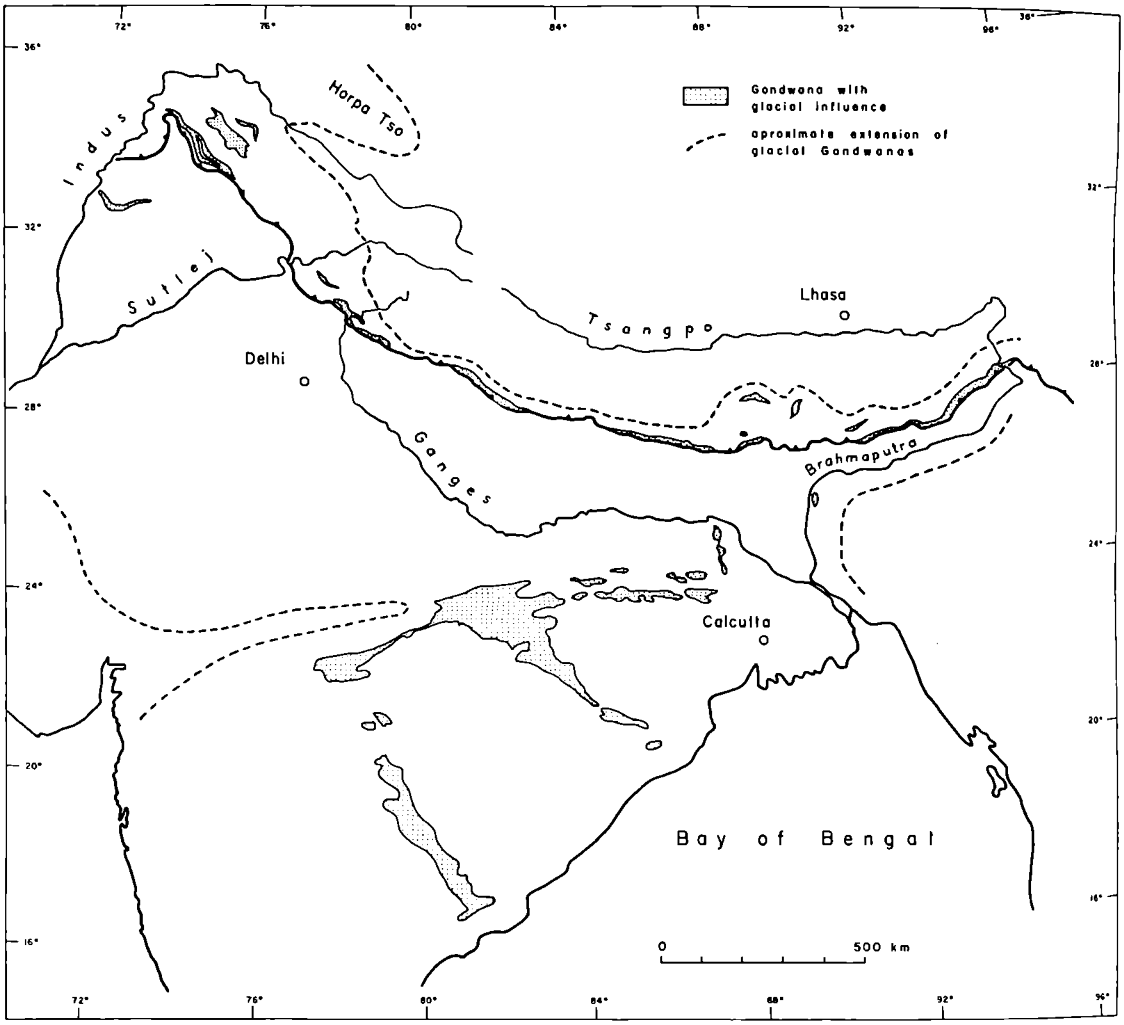


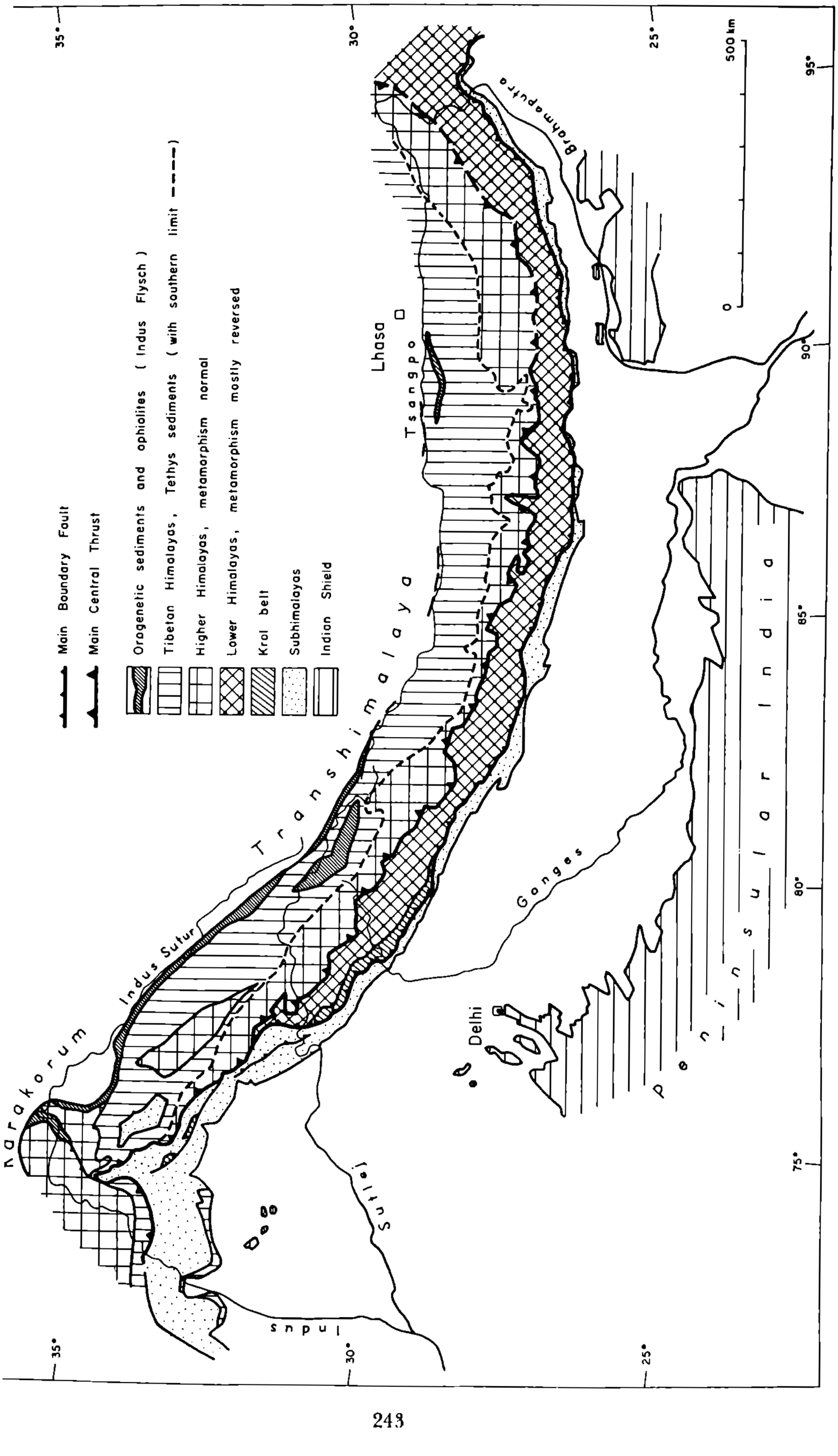
Fig. 144 *Distribution and northwards extension of Gondwana sediments with glacial influence*

as the Krols follow directly above the Upper Carboniferous and must represent the uppermost Palaeozoic, and probably part of the Mesozoic. In the Higher Himalayas rocks of this age are famous for their abundant and well-preserved fossils.

The post-Blaini *Krol rocks* form an outer belt along the Lower Himalayas, and have been observed from the Simla area on the Sutlej River as far as Naini Tal in Kumaon. Towards the WNW the peculiar Jammu limestones, seen in the inliers within the Tertiaries south of the Main Boundary Fault, may be the equivalent of the Krol limestones, while in the Lower Himalayas of Nepal some of the sediments related to the Piuthan nappe of HAGEN may still represent Krol-type deposits. The environment of deposition of the Krol sediments must have been similar to that of the older rocks (late Precambrian to Cambrian) of the Lower Himalayas. The surprisingly large amount of detrital quartz together with thick deposits of unfossiliferous pure limestones leave us here with the same unsolved problems.

The Krol rocks are clearly thrust over the Siwaliks, and thus belong to a facies belt which originally lay further to the northeast of the autochthonous and parautochthonous foothills. They may have been thrust from the more central Tejam belt, where there are now only older, but lithologically similar types of sediments lying below the large crystalline thrust sheets. Their original area of deposition must have been rather extensive, since the Jammu limestones, which can be correlated with the Krol limestones, occur south of the Main Boundary Fault. It seems most likely that the present Himalayan trend, running from the Sutlej River to the northwest, does not follow the outlines of the Krol basin, which was

Fig. 145 *Main structural features of the Himalayas*


Main Boundary Fault
Main Central Thrust
Orogenetic sediments and ophiolites (Indus Flysch)
Tibetan Himalayas, Tethys sediments (with southern limit)
Higher Himalayas, metamorphism normal
Lower Himalayas, metamorphism mostly reversed
Krol belt
Subhimalayas
Indian Shield
Karakorum
Indus Sutur
Transhimalaya
Lhasa
Tsangpo
Brahmaputra
Ganges
Delhi
Sutlej
Indus
Peninsular India
500 km
0
35°
30°
25°
75°
80°
85°
90°
95°

more WNW aligned, crossing the direction of the Main Boundary Fault and continuing, though offset, into the region of the Jammu Hills. This trend would parallel the equally oblique belt along which the Tethys sediments must have passed from the Higher Himalayas into the Kashmir area, crossing the axial crystalline of the northwestern Himalayas. These possible trends are indicated on the enclosed sketch map, Fig. 145.

A large amount of the original rocks of the Krol belt must have been removed prior to the Eocene transgression. The Eocene (Subathus) rests with a marked unconformity above late Precambrian Simla slates and Shali-type rocks of the autochthonous to parautochthonous windows in the Lower Himalayas, or covers the limestones of the Jammu Hills in the Sub-Himalayas above an intervening bauxite level which indicates a prolonged exposure of the underlying rocks. The Eocene rocks also transgress onto the intermediate Salt Range, covering progressively older beds from the west towards the east.

In the Higher Himalayas, as well as in the *Tethys or Tibetan Himalayas*, rock sequences reminiscent of the Krol belt are unknown, and we find a continuous deposition of fossiliferous beds from the Cambrian into the Cretaceous and Lower Eocene with faunas belonging to the Tethys sea. These beds must have been deposited in an environment completely different from that governing the area of the Lower Himalayas, and this clearly supports the large displacement accorded to the Main Central Thrust which has narrowed the gap between the original depositional areas by more than 100 km. *The striking difference between the sediments north and south of this main thrust is a most important fact in the Himalayan geology.* It reflects the difference between the northern margin of Peninsular India, with its large gaps in the sedimentation and its conspicuous Gondwana influence, and the southern border of the Tethys basin.

With the beginning of the Middle and Upper Palaeozoic, and yet more pronounced in the Mesozoic, the sediments become lithologically well-differentiated, and competent beds alternate with conspicuously incompetent shale sections representing larger sedimentary cycles (Permian, Triassic and Jurassic). These sedimentary differences are responsible for independent tectonic movements during the young Himalayan phase and result in complicated folds and south-directed thrusts which involve the sedimentary cover only and are not reflected in the deeper crystalline basement from which part of the sediments have been sheared off. Within the northern Himalayas the generally continous sedimentation up to the Cretaceous was interrupted locally by epeirogenic movements, but not by orogenic episodes. The sediments are mostly shallow marine, but frequently pelagic with ammonite-rich horizons. These sediments do not reflect a deep geosynclinal alignment, but rather a wide shallow platform, or at the most mio-geosynclines.

These conditions seem to have changed with the Cretaceous. After the Spiti shales with their famous ammonite faunas, there follow thick deposits of marine, glauconitic sandstones grading into sediments reminiscent of Alpine Flysch. The only difference is the evidence that, coupled with the Upper Cretaceous Flysch sedimentation, there was a pronounced basic submarine volcanic activity comparable to that which introduced the ophiolites to the Alpine Bündnerschiefer trough, but which is not found in the Alpine Flysch basins. The famous exotic blocks of southern Tibet slipped into this Upper Cretaceous Flysch basin and were later partly thrust upon it. The exotic blocks are well developed in the Tibetan Kumaon Himalayas and remain one of the greatest puzzles of Himalayan geology. The Permian, Triassic and Jurassic blocks are of facies types unknown in these areas, and must have been deposited in basins originally situated between the Himalayas and the Transhimalayas south of the Tibetan mass. Only the tectonic suture line (dealt with in the next section) remains on the site of these mysterious basins.

The Cretaceous sediments reflect the incipient Himalayan orogeny. Movement began earlier in the north, as is witnessed by the transgressive Upper Cretaceous conglomerates of the Reshun-type (Karakorum), which are remarkable for the absence of metamorphic or igneous components. The pebbles have been stretched by later movements. The Flysch character persists into the Eocene and is well exposed along the Upper Indus Valley as the Indus Flysch. With the end of the Eocene, marine conditions must have ceased north of the Himalayas and the rise of the Tibetan platform began before the main Himalayan orogeny. The large consequent rivers began to flow, subsequently cutting through the growing Himalayas.

South of the Himalayas we have noted that marine Eocene sediments are transgressive in the Salt Range, the Jammu Hills and over the old slates which outcrop in the windows of the Simla area. These Eocene beds must have been laid down during a local marine incursion following a strong denudation of the older sediments. Only in the NW Himalayas was the Eocene followed by brackish to freshwater Miocene deposits (the Murrees) which were mostly derived from the Peninsular shield, and only locally from the Himalayas. Molasse-like Siwalik deposition did not follow until the main Himalayan orogeny reached the southern areas and strong erosion began. The Siwalik basin was a narrow depression parallelling the Himalayan chain and bordering

the northern Peninsular shield, from which a considerable amount of detritus was still received. Some of the sediments were distributed along rivers running parallel to the incipient Himalayan ranges (the Indobrahm). It was not until the upper Pliocene and earliest Pleistocene that the main orogenic Himalayan phase produced the Siwalik conglomerates, which in contrast to the older Siwaliks formed local fans.

The first major Himalayan glaciation began during the culminating phase, and the overthrusting of the Siwaliks was followed by fluvioglacial deposition which generally produced boulders much larger than those of the Siwalik conglomerates. The formation of such boulders persists into the Recent gravel fans and terraces and is related to the last marked and still active morphogenic uplift of the main range.

REGIONAL STRUCTURAL OUTLINE OF THE HIMALAYAS

Having studied the geological history of the Himalayan ranges we have reached the picture of their present-day magnitude. Their structures as we see them today have been discussed in the previous chapters within geographically limited areas and we may now summarize the tectonic outline of the whole range. We have distinguished the following major units:

1. Structures of the Siwaliks
2. Main Boundary Fault
3. Structures of the Lower Himalayas
4. Structures of the Higher Himalayas and Main Central Thrust
5. Structures of the Tibetan or Tethys Himalayas
6. Indus Suture Line and the structures of its related rocks

STRUCTURES OF THE SIWALIKS

Contrary to the opinion held by some authors, the Siwaliks form structures with a normal and not a reversed sedimentary column. Wider basin-like synclines alternate with steep, often faulted, assymetric anticlines. Their axial planes, as well as the strike faults on their limbs, are steep at the surface, but probably dip more gently northwards (towards the mountains) at depth, and eventually enter bedding planes. Imbrications do occur, but are not regionally present. Frequently the younger beds (Upper Siwaliks) outcrop towards the north along the Main Boundary Fault, and older, frequently monoclinally folded Siwaliks outcrop further to the south. Their southern limit is mostly erosional and their extension is masked by the large recent fans of the Ganges alluvial deposits. Locally, thrusting of the outer, mostly older, Siwaliks over Quaternary beds can be seen. Folding is often more severe in the older Siwaliks than in the more conglomeratic younger beds, a fact related to the different lithologies rather than to progressively weaker tectonic movements in the younger deposits.

Folding and faulting in the Siwaliks is of early to middle Pleistocene age, and must have preceded the overthrusting of the Lower Himalayas along the Main Boundary Fault. The strike of the Siwaliks does not always conform to that of the fault, and in fact marked divergence can be noted. The local warping of the Main Boundary Fault seems to coincide with areas of reduction of the Siwaliks by erosion subsequent to their folding but prior to the overthrusting. The thrust movement must have occured over a rather uneven erosional surface, which would suggest relief thrusting for certain areas.

Nowhere do the Siwaliks normally overlap the Lower Himalayas north of the Main Boundary Fault. They are sharply and unequivocally overthrust by the pre-Siwalik rocks of the Lower Himalayas, and do not form a normal cover for these ranges. Based on the configuration of the Main Boundary Fault one must accept an average of 25 km for the amount of thrusting, although no windows with Siwalik outcrops are so far known. This displacement would add a considerable section of Siwalik material at present concealed by the Himalayan thrusts, but, on the other hand, it seems most probable that the Siwaliks thin rapidly towards the north.

It is interesting to compare the bulk of the Siwaliks with the volume of the present Himalayas. To the visible bulk of the Siwaliks one must add the amount of the Siwaliks hidden under the Himalayas, as well as the part covered by the alluvial plains. Yet, based on certain assumptions which are admitedly very weak, one obtains a total bulk sum which is only a very small part of the visible volume of the present Himalayas. This observation is in striking contrast to the Alps, where the northern Molasse alone equals the bulk of the adjoining Alps, while a similar amount has been deposited into the Po depression—a deep *hole* in the Alpine hinterland. Conversely, in the Himalayas the hinterland is a high elevated mass lying in the north, which is drained by southwards-flowing rivers, the largest of which cut through the whole range exactly where the highest topographical elevations occur.

MAIN BOUNDARY FAULT

The northern edge of the Siwalik Molasse is a clearly outlined tectonic feature, which was recognized by the earliest investigators. Generally regarded as a steep north-dipping fault, it is more likely a thrust which flattens in depth. It forms the southern limit of the Lower Himalayas, but does not always carry the same tectonic elements. Secondary faults or thrusts branch off the Main Boundary Fault, as for instance in the southern Punjab, where they separate the Siwaliks from the Murrees, or as in the region south of Simla. These secondary fault zones always diverge in a westwards direction and merge with the main fault towards the east. For over 400 km the Krol thrust sheet coincides with the Main Boundary Fault, whilst in some places (southeast Nepal), the higher, more interior, crystalline thrust sheets lie in contact with the Siwaliks. Gondwana formations, particularly the Damudas, are frequently wedged between the Main Boundary Fault and the next higher, and more interior thrusts. While no windows with outcropping Siwaliks have been observed within the Lower Himalayas, the Damudas and/or the Eocene Subathus do occur in well-outlined tectonic windows below older rocks. These windows clearly document the flattish inclination of the thrust. Some Eocene in the Shali window is over 35 km away from the Boundary thrust, and the Damudas in the Rangit River window in Sikkim outcrop after being covered for 30 km by older Dalings. Along the frontal outcrops the Main Boundary Fault and the more interior thrusts show a similar dip and run mostly parallel to each other. This fact supports the idea that also the outermost Main Boundary Fault develops into rather flat thrusts and covers the Siwaliks for an assumed distance of 25 km.

STRUCTURES OF THE LOWER HIMALAYAS

Between the Main Boundary Fault and the Main Central Thrust lies the stretch of the Lower Himalayas, which to the southeast of the Punjab are still tectonically little understood because of the lack of stratigraphical control. We have seen that a border facies of the Peninsular Shield makes up a large percentage of the formations of the Lower Himalayas. The primary differences in metamorphism, reflecting the history of the shield rocks, were superimposed by the metamorphism of the young Himalayan phase. The striking changes in metamorphism are, however, *mostly restricted to the older rocks*, and so far in the Himalayas no higher grade metamorphism has been observed in formations younger than Ordovician. Only along the ophiolitic belt, the Tibetan zone and in the Karakorum are younger beds (Jurassic of southern Tibet, Permo-Carboniferous in the Karakorum) affected by higher grade metamorphism. As we shall see, the Himalayan metamorphism which produced migmatization and finally young mobilization resulting in tectonically unaffected tourmaline granites was restricted to the previously metamorphosed sections of the crystalline thrust sheets. The youngest granites, intruding even Mesozoic sediments, hardly produced any marked contact metamorphism, and certainly no regional metamorphism.

All along the Main Boundary Fault we can observe severe tectonization. This important structural zone is not a sharply defined feature, though its southern contact, a steep thrust against the Siwaliks, is generally sharp. The thrust mass which follows just north of the Siwaliks is extremely sheared and is cut by a multitude of secondary faults and steeper thrust zones. The strong tectonization is well displayed in the complicated foothills of Bhutan. It is within this tectonized zone along the Lower Himalayan south border that independent thrust sheets have developed, such as the Krol thrust which extends for a distance of over 400 km from the Sutlej River in the NE to beyond Naini Tal in the SE. Corresponding thrust sheets along the Nepalese foothills do exist, but their relations with the Krols are not yet ascertained. The Baxas in Bhutan are similar thrust masses, but here too, they seem to correspond to older formations which are not directly comparable to the Krols. The Krol thrusts are generally normal thrust sheets, and not reversed recumbant folds as assumed by some authors.

From the south to the north, or from the outer region towards the inner zone of the Lower Himalayas, succeedingly older thrust masses appear. Where the Krol thrusts are not developed, a band of steeply thrust Gondwana rocks can be observed along the whole length of the Nepalese foothills and extending through Sikkim and Bhutan into the frontal thrust regions of the NEFA Himalayas. It seems possible that the Gondwana thrust zone, with its Damuda rocks, is mostly reversed. It is followed inwards by further thrusts with older, mostly Precambrian to early Cambrian rocks, well documented by the thrust Daling schists. The frontal thrust is generally steeply north-dipping, but flattens in depth, as is witnessed by the most interesting Damuda rocks in windows in inner Sikkim, over 30 km from the frontal Daling thrust.

The structures of the older, inner thrust masses of the Lower Himalayas depend mostly on the lithology of the involved formations which may show considerable regional variations, such as the schistose Dalings of Sikkim to the thick-bedded Deoban limestones of the Kumaon Lower

Himalayas. Not all the outcrops of the inner zone of the Lower Himalayas are thrust masses and some of the Simla slates with their transgressive cover of Eocene seem to be parautochthonous. The enormous stratigraphical hiatus and strong unconformity seen in these may represent the history of a southern belt, which is not separated from the corresponding shield rocks except by the overthrust Siwaliks in some areas. The peculiar outlines of the Jammu limestones, south of the Main Boundary Fault, which are also transgressed by Eocene, seem to support this idea. They indicate that the corresponding facies belt does not run parallel to the present structural outline of the range.

The huge masses of limestones and quartzites in Inner Kumaon, where they form the deepest outcrops, have been regarded by some authors as more or less autochthonous windows. But comparing their facies with the above mentioned parautochthonous windows where the Eocene transgression is a most important character, a striking difference is evident and I am more inclined to consider the thick pile of sediments with its gentle folds as thrust allochthonous masses. AUDEN's section with the underlying Eocene relics supports this idea (Fig. 146). Autochthonous shield-type elements have hardly the relatively gentle tectonics displayed by some thrust masses, but reflect more closely the massif-type steep tectonic style (Simla windows). This criterion should, of course, not be applied indiscriminately, but in many thrust mountain ranges one discovers that thrust masses, except for their transported older structures, as for instance in the Silvretta crystalline of the Alps, do contrast strongly with autochthonous or parautochthonous rocks, which generally display a steep, often fan-like structure, chacarteristic for older massifs. As in the Kumaon, the writer also believes that most of the Nepalese Lower Himalayas, placed under the general term of Navakot, belong to allochthonous thrust sheets and not to folded autochthonous rocks. This assumption differs with some of the more recent views expressed on the Nepalese Lower Himalayas.

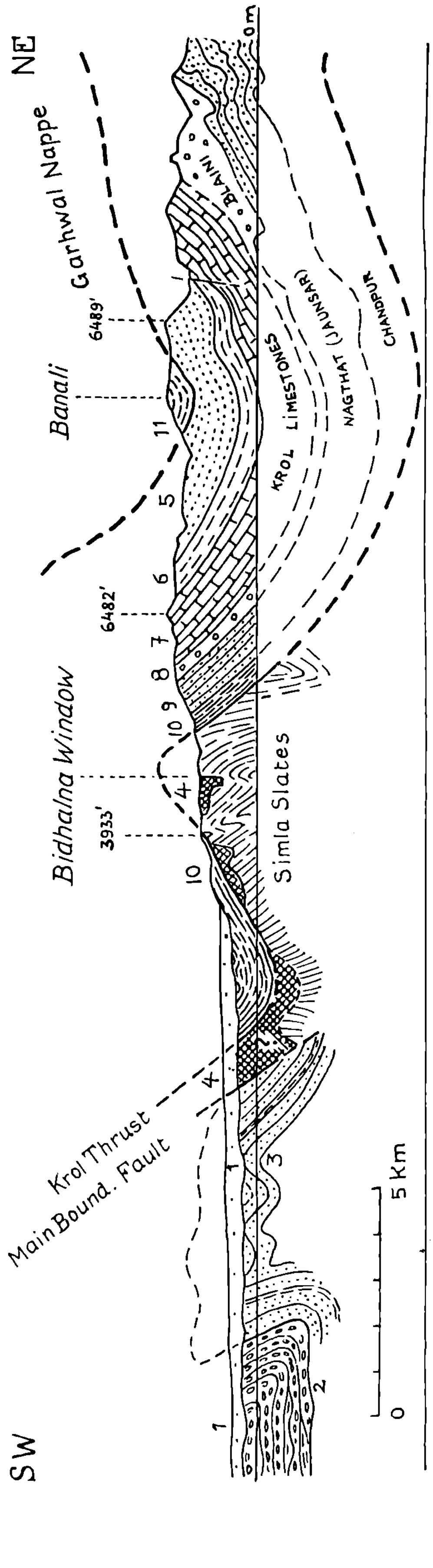


Fig. 146 *Section across Bidhalna window and Banali outlier* in Theri State (Kumaon); redrawn after J. B. AUDEN (1937)

1 Dun gravel
2 upper Siwaliks
3 lower Siwaliks
4 Nummulitic: calcareous shales and quartzites, transgressing Simla slates
5 upper Tal
6 lower Tal
7 Krol limestones
8 Blaini (boulder beds)
9 Nagthat quartzites
10 Chandpur slates
11 sericite schists

Some of the complicated and often strongly folded structural belts in the Lower Himalayas reflect the older NE-SW-directed structural grain of the Peninsular Shield rocks which have been involved in the Himalayan tectonics. Such aberrant structural trends are frequently observed crossing the main trends which parallel the Himalayan range. They are also responsible for most of the major N-S-directed river gorges of E Nepal and Sikkim. Apart from such clearly defined cross structures, certain culminations and depressions seem also related to a pre-existing older structural grain (the Krol basins of AUDEN, 1935). Certain irregularities in the outline of the frontal thrusts, their frontal lobes and embayments may be related to such an alignment. The Aravalli structural grain was probably also responsible for a selective deposition in the Upper Siwaliks and may even have controled to some extent the post-Siwalik erosion, which, on the other hand, guided the post-Siwalik thrusting along the Main Boundary Fault.

Examples of structural investigation in Bhutan

During the 1963 reconnaissance work in the Bhutan Himalayas we investigated some of the detailed structural pattern. The preliminary results are shown in Fig. 147, which also represents a generalized tectonic map of Bhutan. On it the fold axes and major lineations are indicated. On this sample the structural pattern is analized for the Lower as well as the Higher Himalayas of Bhutan.

In the highly sheared rocks of the Baxa-Daling foothills the fold axes change from NW, through north into a NE direction. In the Chasilakha gneiss zone the trend turns sharply again towards the NW and even W, which is also the general direction of the axial plunge. In the Paro metamorphic belt, which runs in an east-west direction through the central part of Bhutan we note N-S fold axes. The anticlinorial feature of this belt is shown by the south plunge of the more southern cross axes and the consistent northwards-directed plunge of the northern axes near the contact with the large Takhtsang gneiss sheet. Not only the fold axes but also the striation of the schists and gneisses as well as the alignment of porphyroblasts is N-S directed. The pronounced N-S grain of this metamorphic belt may reflect relic but reactivated N-S structural features probably related to the tectonics of the shield, which, south of Bhutan, is depressed by a N-S graben structure lying between the Shillong uplift in the east and the Rajmahal traps in the west (Ganges-Brahmaputra graben).

The rather rare small-scale structures in the Takhtsang gneiss sheet further to the north are again NW directed and the folds plunge in the same direction. In the sedimentary Lingshi basin we note axial folds striking east-west with a western plunge, while in the more northern outcrops they plunge towards the ENE. At a first glance this marked difference between the strike direction of the fold axes within the non-metamorphic sediments and the north-south strike in the metamorphics is evident.

In the northern part of central and eastern Bhutan (north of Bumtang) N to NNW plunging axes characterize the metamorphic belts, while some of the larger marble zones (Tsamba marbles) as well as the flat adjoining gneiss sheets expose westwards as well as eastwards plunging axes.

From our preliminary structural analysis we may deduce that the larger, gently folded gneiss sheets as well as the unmetamorphic sediments in the north have mostly an east-west oriented structural grain, while the complex east-west running metamorphic belts show an intense north-south directed structural pattern.

Reverse metamorphism and its significance

Besides the varied sedimentary rocks of the Lower Himalayas, large stretches of this mountain section are covered by crystalline sheets in which sillimanite-bearing garnet gneisses dominate. Granitic masses occur locally in some of these gneisses. All along the Lower Himalayas (Kashmir excepted) these crystalline sheets form the structurally (and topographically) highest elements, and it is a well-known fact, observed as long as 80 years ago (see p. 90), that the regional metamorphism increases from the bottom upwards, so that we find non- or only low-grade metamorphic sediments in the deepest outcrops, and these become increasingly metamorphic upwards. Usually the thrusts are placed at the base of such gneiss sheets, but, as we have noted, it is often most difficult to decide just where to place such a thrust within these often transitional sections. The change from non- or epi-metamorphic Daling slates into meso-schists and then into kata-metamorphic Darjeeling gneisses is by now a classic example. We have further seen that these alterations are not influenced by any appreciable amount of introduced matter, but that the metamorphism can be explained by increasing temperature and stress alone.

It is much more difficult to understand the structural significance of this reversed metamorphism. The problem may be stated as follows: does the reversed metamorphism affect otherwise structurally normal rock sequences, or are the sections equally reversed? Unfortunately little attention has so far been given

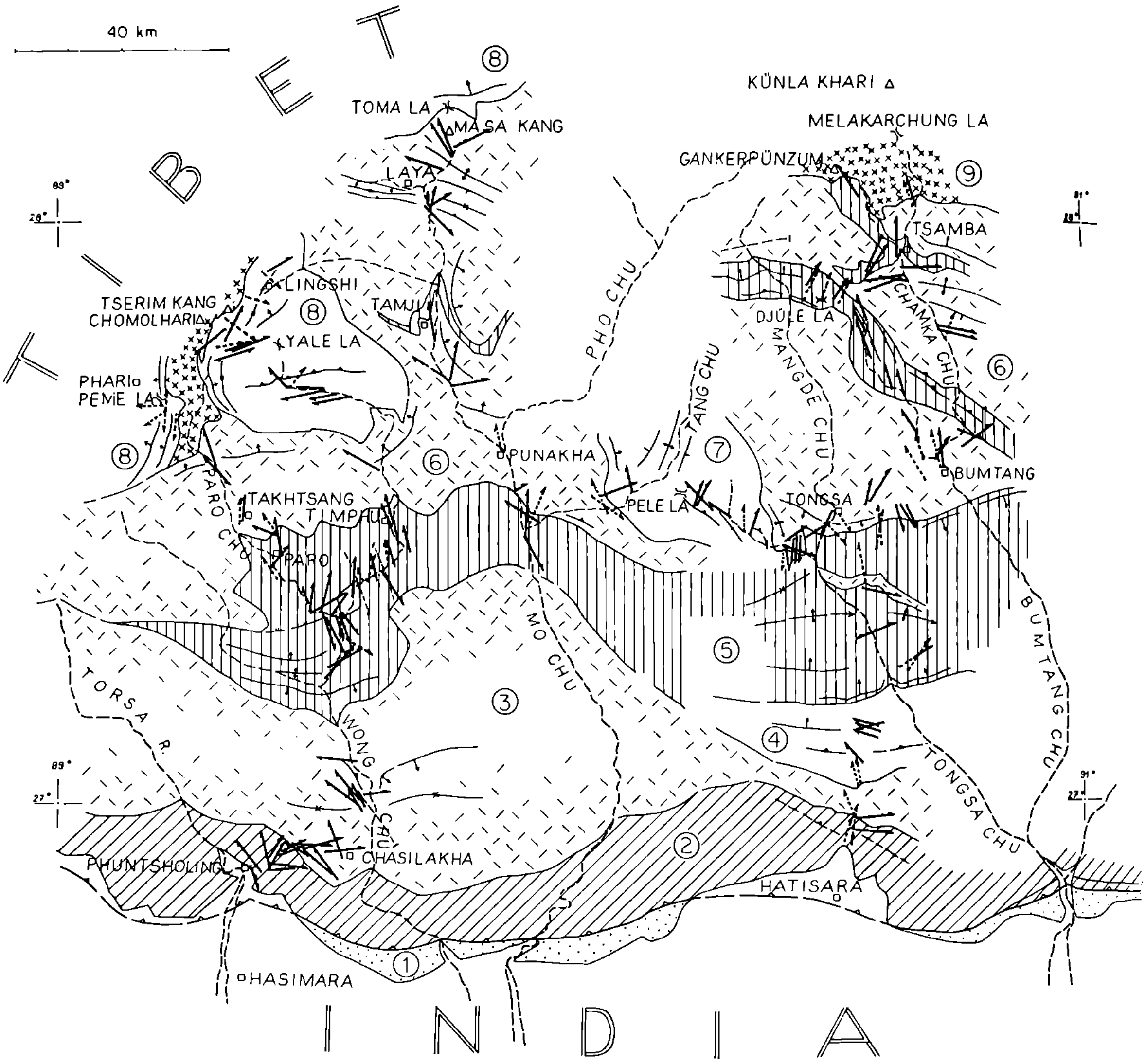


Fig. 147 *Structural sketch map of Bhutan* with special emphasis on lineations; original by A. Gansser

1 Siwalik belt
2 Baxa-Daling foothill belt
3 Chasilakha-Soraya gneiss sheet
4 Quartzites and phyllites of Sangsing-La
5 Paro metamorphic belt
6 Takhtsang gneiss sheet
7 Tang-Chu Paleozoic sediments
8 Mesozoic and Paleozoic Lingshi basin including the sediments of Phari and north Masa Kang
9 Chomolhari tourmaline granites

full arrows = fold axis, dotted arrows = lineations

to such questions. In some areas (eastern Kumaon) we know that large sections of sediments underlying the gneisses are in a reversed position. On the other hand, definite proof exists that some sections which become increasingly metamorphosed upwards are structurally normal.

A reversed section combined with upwards increasing metamorphism leads to the assumption that large recumbant folds would explain the facts. Such suggestions were already ventured nearly one hundred years ago for the Darjeeling region (Fig. 148) and reappear in some recent publications. Recumbant folds could be visualized in such areas where reversed metamorphism is coupled with a reversed geological sequence, but it is not applicable where a reversed metamorphism is imprinted on or coupled with normal sections. We recognized that the Krol belt, for instance, consists of normal thrust sheets and not of recumbant folds. In Auden's overthrust Garhwal nappes the metamorphism is reversed, but here the contact with the underlying Krol thrust sheets is rather sharp.

STRUCTURES OF THE HIGHER HIMALAYAS AND MAIN CENTRAL THRUST

In most of the published geological sections through the Himalayas the crystalline thrusts covering the less metamorphosed sediments of must be traced *below* the main thrust. The enclosed regional section (A on Pl. II) is interpreted accordingly. In accepting a direct connection—an interpretation also used by the writer 28 years ago—we come to the dilemma of connecting a crystalline mass with a pronounced reversed metamorphism (Lower Himalayas) with

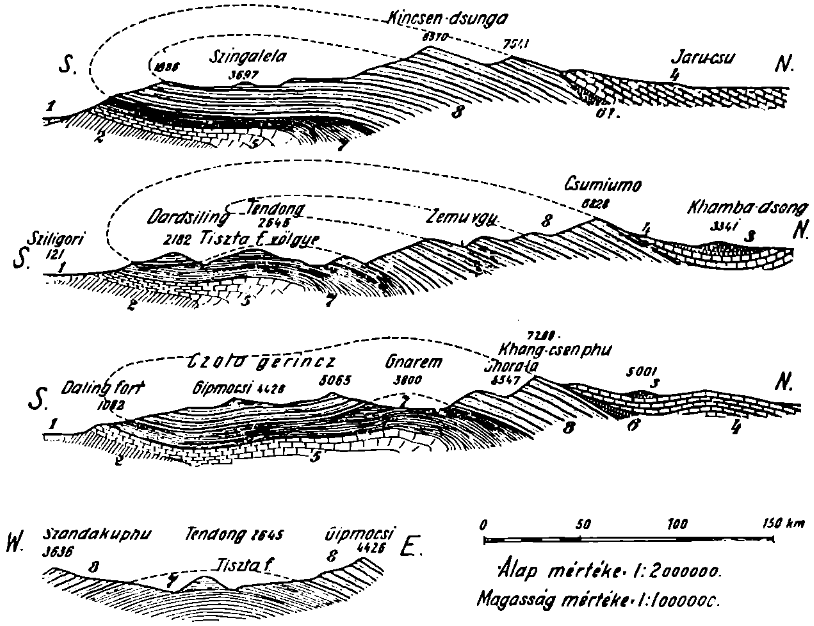


Fig. 148 *The recumbant folds in the Sikkim Himalayas* by L. v. Lóczy 1907 (observed 1878)

the Lower Himalayas are shown as klippen-like remnants of the Main Central Thrust sheet, which forms the base of the Higher Himalayas. We have recognized, however, that within the crystallines of the Higher Himalayas the regional metamorphism generally decreases upwards, and that the top part of the Main Thrust sheets, where the metamorphism is of a much lower grade, is covered conformably by fossiliferous sediments, beginning in many places with the Cambrian. Within the Higher Himalayas the sedimentary cover is generally non-metamorphic or has undergone only low-grade alteration. Local higher metamorphism in younger sediments (Jurassic) is observed mostly outside the actual Himalayan range (southern Tibet). Except for two known localities, the crystalline sheets of the Lower Himalayas lack the corresponding cover of the Main Himalayas. We must realize that a direct connection of the crystalline thrust sheets of the Lower Himalayas, such as the Almora thrust mass, with the Main Central Thrust mass of the Higher Himalayas is not possible, and that the Lower Himalayan crystalline a crystalline mass in which the metamorphism decreases normally upwards and which is covered by conformable fossiliferous sediments. The dilemma is intensified by the difference in the crystalline rocks in the two thrust sheets.

The Higher Himalayas, with their immense, often over 10 km thick basal crystalline sheet, have a rather simple tectonic picture. This huge thrust sheet supports the Higher Himalayan sediments, which, as far as the Lower Palaeozoic sections are concerned, follow conformably over the schists. Once the sediments become better differentiated, however, they display a more independent tectonic style. This somewhat oversimplified picture has not yet been verified for the whole length of the Himalayan range. In Sikkim and Bhutan, where the Lower Himalayas consist predominantly of crystallines (Darjeeling type gneisses) a clear division between Lower and Higher Himalayas is somewhat arbitrarily traced. Furthermore, structural cross features complicate the regional outline. In the southern slope of Kangchendzönga, for instance, it is difficult to distinguish that part of the crystalline

belonging to the Darjeeling gneisses and gradually developing from the Dalings by reversed metamorphism from that of the thrust sheet of the Higher Himalayas, which, in the Jongsang Peak north of Kangchendzönga, is normally overlain by sediments of the Everest type.

Problem of the metamorphism

Investigations of the main crystalline thrust sheet of the Higher Himalayas have hardly begun, and very little is so far known of tho interior configuration of these immense crystalline masses. Thick members of quartzites and a conspicuous zone of marbles, alternating with psammitic gneisses, are widely distributed and are often accompanied by a prolific swarm of acid dyke intrusions. Progressive granitization plays an important role, as is well documented in Nanga Parbat, and may finally produce the widespread young intrusive tourmaline granites which cut through all previous structures and which have not been affected by later movements. A late to post-orogenic emplacement is thus well documented, but despite this and the certainty that the migmatization is rather young, no appreciable regional metamorphism has affected the Palaeozoic and younger sediments. From what we know so far of the whole Himalayan range, the metamorphism of mostly higher grades remains restricted to the Precambrian rocks. This distinguishes the Himalayas from the Alps for instance, where, in restricted areas, medium grade metamorphism reaches Cretaceous sediments of the eugeosynclinal belts. In the mountain ranges of Central Iran too, medium to high-grade metamorphism affects the Jurassic and locally some Eocene. This metamorphism may be comparable to some of the metamorphism of the Jurassic sediments which form the so-called "Northern Range" in southern Tibet, north of the Everest region. As we have seen in the regional introductory notes, the structures of Central Iran can be correlated with features belonging to the Hindu-Kush and partly to the northern Karakorum-Pamirs, where metamorphism of Palaeozoic and younger sediments is known to exist.

The young metamorphism, the migmatization and the granitization of the crystalline rocks of the Himalayas is reflected in the few available, but illuminating absolute age determinations of Himalayan rocks. So far micas have been investigated by the potassium-argon method. Some of the samples collected by LOMBARD from the Everest region were determined by KRUMMENACHER (1961) while the micas of a few pegmatites and meso-metamorphic muscovite quartzites collected by the author in Bhutan were investigated by P. SIEGNER in Baltimore.

The mica age of the various samples is listed below:

Preliminary Bhutan age determinations by P. SIEGNER:

Muscovite quartzite, N of Paro (mu): 9 ± 2 m.y.

Muscovite pegmatite, W of Tongsa (mu): 12 ± 2 m.y.

Muscovite-biotite pegmatite, W of Tongsa (bi): 11 ± 2 m.y.

NE Nepal age determinations by D. KRUMMENACHER:

Micaceous quartzite, Nawakot nappe (detrital mu): 728 ± 2 m.y.

Sericite phyllite, Katmandu nappe (sericite): 15.9 ± 0.6 m.y.

Metamorphic arkose, Katmandu nappe (bi): 16.4 ± 1.2 m.y.

Quartz-diorite gneiss, Katmandu nappe 5 (bi): 12.9 ± 0.2 m.y.

Diorite gneiss, Khumbu nappe (bi): 9.8 ± 0.1 m.y.

Migmatitic diorite, Barun gneiss (bi): 9.8 ± 0.9 m.y.

Pinite-biotite gneiss, Namche Bazar migmatites (bi): 10.5 ± 1 m.y.

Biotite gneiss, Namche Bazar migmatites (bi): 13.3 ± 0.6 m.y.

Dioritic biotite gneiss, Khumbu nappe (bi): 14.6 ± 1.8 m.y.

Amphibolite, Khumbu nappe (bi): 14.8 ± 1.5 m.y.

Dioritic biotite gneiss, basal Tibetan series (bi): 17.6 ± 0.3 m.y.

Dioritic biotite gneiss, basal Tibetan series (bi): 13.5 ± 0.4 m.y.

Alkali biotite granite, Tibetan series (bi): 16.8 ± 1.6 m.y.

Tourmaline quartzite (Nuptse), upper Tibetan series (bi): 16.5 ± 1.6 m.y.

Biotite sericite schists, Tibetan series between South Col and summit of Everest (bi): 17.3 ± 0.6 m.y.

Most of the micas determinded from LOMBARD's samples belong to migmatites of the Everest region and show a young mica age. The age given by the detrital micas from a quartzite belonging to the Nawakot sediments differs from these, and its Precambrian mica age seems to indicate that no major thermal alteration has taken place. A remarkable hiatus in the orogenic

history of the Himalayas seems to be reflected by this fact, but it is admitedly represented by only a single sample.

The muscovites and biotites from Bhutan are from pegmatites cutting the migmatitic gneisses of the basal part of the Higher Himalayas. The muscovites from the meso-metamorphic (kyanite) quartzites of Paro are a product of the late orogenic metamorphism, or at least have been affected by higher temperatures related to this phase.

If we look at similar mica ages from the cores of the Alpine nappes (the Lepontic or Ticino gneisses), where the latest thermal effect is expected, the Himalayan phase seems to be markedly younger, its 10 million year age comparing with the 17 million years of the Alps. The youngest metamorphism, mobilization and the initiation of the morphogenic phase (the finale of the Himalayan orogeny) were without doubt related to a rising heat front after the main compressive phase was over. But, in spite of these important young phases, the Himalayan metamorphism was mostly restricted to previously metamorphosed rocks. During the orogeny these metamorphic Precambrian rocks were first transported by thrusting, and then suffered a subsequent metamorphism which was sufficient to mask the thrust contacts in the Lower Himalayas, without, however, appreciably affecting the Cambrian and younger sediments. The migmatization and granitization were thus reactions confined to the metamorphic rocks, and excluded from the Cambrian and younger sediments. Here lies one of the most interesting problems in the geology of the Himalayas. This example of how older metamorphic rocks are more easily re-altered by youngest metamorphic phases than their younger sedimentary cover has equivalents in many other crystalline mountain ranges, but its importance has not yet been fully realized.

STRUCTURES OF THE TIBETAN OR TETHYS HIMALAYAS

The crystalline thrust sheet of the Higher Himalayas is normally covered by a great thickness of mostly pelitic sediments which are conformably welded to the schists and form the top part of the main crystalline thrust mass in most sections. Within these argillaceous deposits the epi-metamorphism gradually diminishes, and the first fossils, of Cambrian to Ordovician age appear. It is only in the Ordovician that we find more differentiated sediments (quartzites, shales, limestones) and from here upwards the structural aspect of the sediments becomes more individualized. South-vergent folds and south-directed thrusts and imbrications are the rule, but locally, north-vergent folding can play an important role (northern Nepal). Regionally, the general aspect is still that of a south-directed movement, partly of a schuppen character, and does not support the idea of north-directed gravity slides which some authors suggest as a subsequent phase to the rise of the Himalayas. Towards the western Himalayas, where the range widens and the elevations of the main range decrease, the folding of the Tibetan Himalayas is gentler and more of a Jura-type, such as is seen in the folds of the Spiti area. In the Mesozoic sections with their marked differentiation into plastic shales and thick limestones and dolomites, disharmonic folding is very accentuated.

INDUS SUTURE LINE AND THE STRUCTURES OF ITS RELATED ROCKS

Except in the Kashmir area, the Sub-Himalayas, Lower and Higher Himalayas are made up of elements formerly connected to the marginal part of the Indian shield. Only in the Tibetan Himalayas do we find a geosynclinal influence in the sediments formed in a shallow, gradually sinking Tethys sea. We thus realize that the main Himalayan range has not developed from a geosyncline, and does therefore not conform to the classical theory of Alpine mountain building. With the beginning of the Himalayan orogeny in the Middle and Upper Cretaceous a deep-seated tectonic disturbance occured in the Tibetan Himalayas, and was responsible for the outflow of a large amount of ultrabasic rocks. A corresponding basin must have been outlined at an earlier date, since the sediments of Permian and younger age are unlike all other Himalayan rocks and reflect a totally different facies, probably belonging to a deeper geosynclinal belt. These sediments are seen in the exotic blocks which have already been discussed in some detail (p. 123). Most of these exotic blocks must have slipped during submarine movements related to the outpouring of basic lavas and been intimately mingled with basic flows and marine Flysch-type orogenic sediments. In the northernmost Kumaon Himalayas these olistostromal masses form large thrust sheets, probably *flowing* southwards over the Cretaceous sediments and older rocks. Otherwise these basic masses, with their Flysch sediments are restricted to a narrow belt following north of the western Himalayas along the Upper Indus River, from where the name Indus suture line is derived.

During the main Himalayan orogeny, but probably prior to the formation of the Main Central Thrust, the northern exotic Flysch belt must have been compressed by the underthrusting of the Indian shield against the Tibetan mass,

which at the same time was elevated. Large areas of geosynclinal deposits must have buckled down and disappeared, and this would explain the fact that the depositional areas of the exotic blocks remain so far undiscovered. The end effect was the creation of a sharp tectonic line (the Indus suture line) along which large areas disappeared and which is comparable to the Alpine root zone and the Tonale line. During the same compression the northernmost Flysch with exotics and basic rocks was thrust northwards against the autochthonous foreland of the Transhimalayas, and is now well displayed south of the Kailas Range and north of the Tso Morari uplift. This counterthrust is the only larger northvergent tectonic feature of the Himalayan range.

The whole of this most important tectonic element, characterized by Flysch-type sediments and basic rocks, can be traced from the western Himalayan syntaxis, where it borders the Nanga Parbat uplift and is cut by the Karakorum thrust, to the southeast and east as far as the holy lake of Manasarowar (Ph. 95). Just to the east of this we note the probably autochthonous Gurla Mandhata gneiss dome, the *en echelon* continuation of the Chilamkurkur uplift and most likely an equivalent of the Tso Morari gneisses in the west. The Gurla Mandhata dome interrupts the strike of the Tethys sediments and the further connection towards the east is lost. The eastern continuation of the Indus suture line is so far unknown. However, we have noted that basic rocks appear in southern Tibet north of Sikkim, and are associated with an incipient metamorphism of the Jurassic sediments. Further east the Tsangpo forms a conspicuously straight morphological feature, not unlike the Upper Indus in the northwest, and one could venture the idea that the Tsangpo follows a major structural element. Unfortunately, no geological information of these areas is available, and our theories remain fully in the air. We have, in a most tentative way, indicated this possibility on the regional tectonic map, Pl. I B.

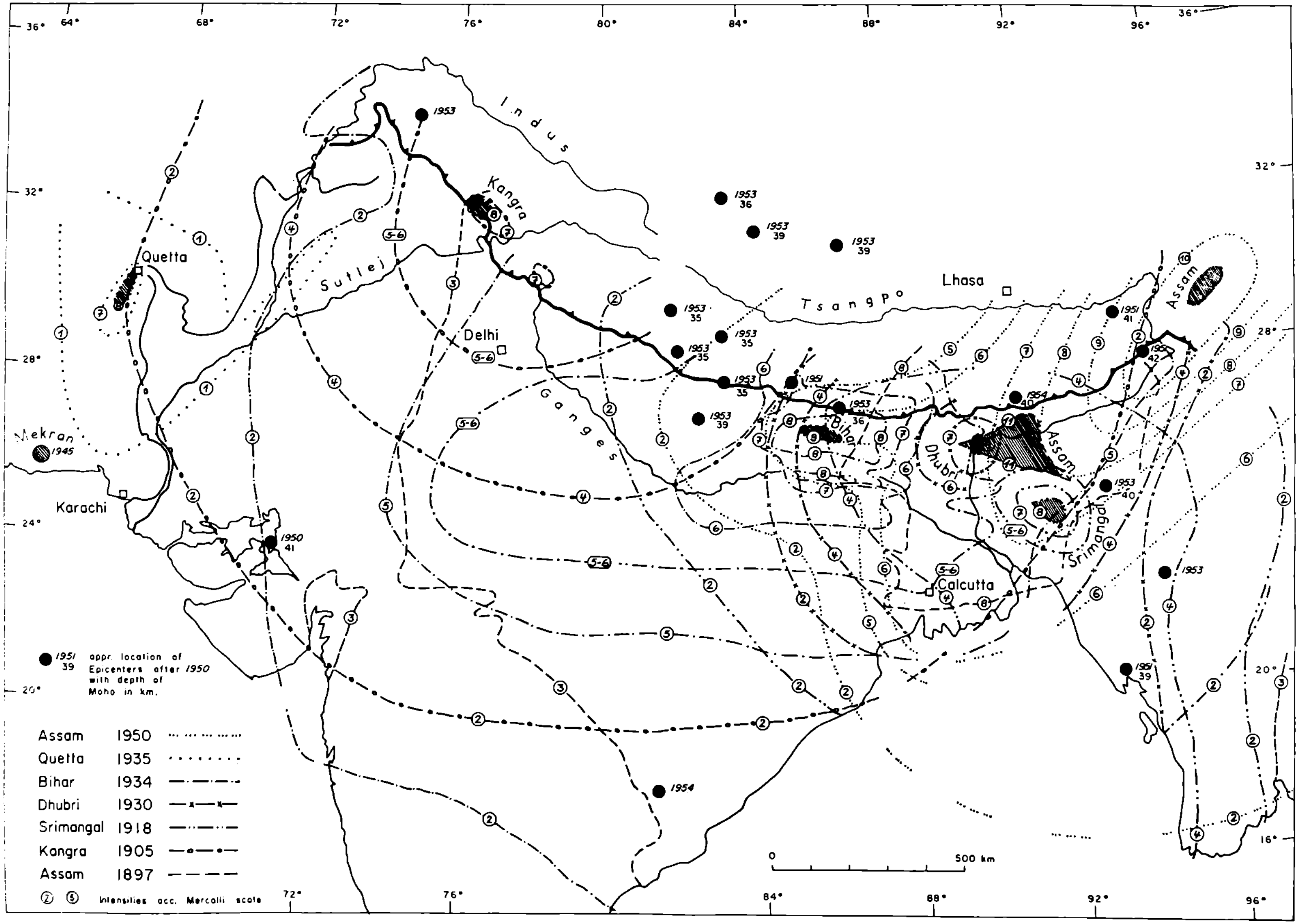


Fig. 149 *Major earthquakes of the Himalayas and adjoining areas*, compiled from all available sources

REGIONAL SETTING

If we review the regional setting of the Himalayas in the light of our previous discussion, we note some striking particularities, such as their outstanding height, the thrusts, rock composition and their isolated position. The Himalayas have no direct continuation either towards the west or to the east. The singular syntaxial bends on both extremes preclude a straightforward continuation of the Himalayan elements.

In the west, the Sulaiman Range is not a direct continuation of the Lower Himalayas, but is a fold system of younger sediments (Mesozoic and younger) which develops out of the Hazara Ranges in the west. Westwards, the Sulaiman belt is sharply limited by an ophiolitic tectonic line from the Flysch-type Baluchistan and Afghan sediments. This suture line may be a continuation, or most likely a branch, of the Indus suture line. The other branch seems to form the southern border of the Hindu-Kush Range, the western equivalent of the Karakorum.

It is much more difficult to follow the eastern continuation of the Himalayas, for here we lack most of the needed geological information. The little we know indicates that here too there is no direct continuation of the range. The south-eastern Assam foothills (Naga Hills) differ from the corresponding Himalayan foothills. The crystalline rocks of the Mishmi Hills seem to belong to the Higher Himalayas, though some indications of inverted metamorphism do exist. The backbone of the western Burmese ranges, the peculiar Arakan Yoma, has no affinities with the Lower or Higher Himalayas. The Flysch-type sediments, mostly of Cretaceous age, expose some ultrabasic rocks aligned along the eastern border which is faulted and partly thrusted. A certain similarity with the Indus Flysch belt seems evident, but no direct connection with this important north Himalayan element is known. We have noted that the latter disappears east of the Manasarowar Lake in the northern Kumaon Himalayas. The Arakan Yoma Range is certainly no eastern equivalent of the Sulaiman Range.

Within the mountain ranges of Asia, the Himalayas display thrusting of such a magnitude that a crustal shortening of about 400 km is suggested. This is not unlike the figure assumed by some authors for the crustal shortening in the Alps. This amount, however, does not include the shortening along the Indus suture line, where a considerable area (the exotic regions) must have disappeared into depth. Except for the northwards-directed thrust of the exotic Flysch masses towards the Transhimalayas southwards-directed tectonic elements dominate. This south vergency is at present underlined by the exceedingly elevated hinterland (the Tibetan Plateau) and the deeply depressed foreland — the Indo-Ganges and Brahmaputra plain. These features offer a striking contrast to the present configuration of the Alps. The picture was probably less accentuated during the major Himalayan orogeny. The final rise of the Tibetan plateau is coupled with the youngest, actually Recent morphogenic rise of the Himalayas, and has as its counterpart the sinking of the Indian foreland.

In the eastern Himalayas, the foothills are steeper and the foreland basin has shrunk to only 30-50 km. It is not without interest to note that most of the larger *Himalayan earthquakes* are concentrated in the eastern Himalayas and their foreland. This fact is illustrated in Fig. 149 where

Phot. 93 *Biotite schists and gneisses form large inclusions in the tourmaline granite of Melakarchung-La.* (View towards the NE) Peaks north of the Tibetan border. N Bhutan (phot. A. Gansser)

Phot. 94 *The famous Künla Khari in the head waters of Kuru-Chu (7600 m).* It seems to consist of gently northwards-dipping gneisses and granite intrusions, forming the very base of the northwards following Tibetan sediments. Biotite schists form the rounded hills below the south wall. View due north. Southern Tibet (phot. A. Gansser)

Phot. 95 *"Map" of the Manasarowar lake and Mt. Kailas.* Old wall painting in Tinkar (NW Nepal) (phot. A. Gansser)

some of the major earthquakes have been compiled. Practically all are of the shallow type, and their foci are believed to occur between 20 and 30 km in depth. This is somewhat less than the presumed depth of the Moho discontinuity, which, based on results which are admittedly vague, varies from 35 km in the western Himalayas to over 40 km in the eastern part of the range. This amount is small if compared with the great crustal depression of the southern Alps, amounting to 70 km, which is probably so far the largest known crustal thickness. The fact that the Himalayas are not a geosynclinal type mountain range, except for the zone of the Indus suture, may be the reason for the relatively shallow crust below this high pile of mostly crystalline thrusts. Deeper depressions may be eventually found related to the Indus suture line.

In the whole Himalayas, upwards movements are still very active. The morphogenic phase is clearly reflected in the present history of the range. The main elevation of the Himalayas was an event witnessed by the earliest men. We may here recall the interesting idea ventured by B. SAHNI that the earliest human migrations were facilitated by a barrier of less forbidding height and steepness than the impressive Himalayas of today.

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Large scale maps are attached to the respective publications.

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GENERALIZED SECTIONS THROUGH THE HIMALAYAS

by A. Gansser

A Kumaon Himalayas

B Western Bhutan Himalayas

C Eastern Bhutan Himalayas

For legend see Plate I A

(m = marble intercalations)

Plate III

GEOLOGICAL SECTIONS through the EASTERN KUMAON HIMALAYAS 1–4

(redrawn and completed after Heim and Gansser, 1939)

1 basic and ultra basic rocks

2 granites (Pre Miocene)

3 granites (Post Miocene)

4 gneisses } with quartzites, marbles and pegmatites (Precambrian)
5 schists }

6 Martoli-Garbyang (incl. Ralam Cgl) (Cambrian?)

7 Tejam Lst, Sl and Sch } (Late Precambrian to Cambrian)
8 Chamoli Qz }

9 Shiala and Muth Qz (Ordovician-Devonian)

10 Productus Sh (Permian)

11 Infra-Krol, Krol and Tal

12 Kalapani-Kioto (Triassic-Jurassic)

13 Spiti Sh (U. Jurassic-Lowest Cretaceous)

14 Giumal Sst and Flysch with exotic blocks, in black (Cretaceous)

15 Kailas Cgl (Eocene?)

16-17 Murrees-Siwaliks (Miocene-Pliocene)

Plate IV

1  1

2  2

3  3

PANORAMA OF EASTERN KUMAON HIMALAYAS

1 Clear division between Lower Himalayas (foreground rolling hills) and Higher Himalayas (high range background). Main Central Thrust at base of higher mountains. Sketch drawn from Jandi hill, N of Almora by A. Gansser. Visible extension of range appr. 400 km. (hights in metres)

PANORAMA OF CENTRAL KUMAON HIMALAYAS

2 (Tehri Garhwal), seen from hill zone E of Mussorie. Snow line coincides approximately with Main Central Thrust, deviding Lower from Higher Himalayas. In foreground Krol type sediments. (Phot. A. Gansser) (hights in metres)

PANORAMA OF EASTERN NEPAL HIMALAYAS

3 From Pt. 3270, north of Okhaldhunga. Photographed by F. Müller. Note the synclinal position of the Everest area and regional rise towards Arun River Gorge. Lower and Higher Himalayas are well defined. (hights in metres)